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An overview of solar assisted air conditioning in Queensland's subtropical regions, Australia

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ABSTRACT

Australia has a very sunny climate, with a very high demand for air conditioning. Relying on electricity to drive, buildings' HVAC systems will cause a significant negative impact on the environment. In this paper, recent developments in solar assisted air conditioning technologies are reviewed and presented. The conceptual basis of the technologies including open and closed cycles cooling technologies, capabilities and limitation are discussed. Energy demand, energy consumption by Australian buildings sector and economic and environmental problems associated with the usage of fossil fuel resources are reported. Second the issue of mould growth and indoor thermal comfort and indoor air quality is highlighted. Finally the technology fundamentals and theories involved with solar energy and solar collector's technologies are summarised and discussed.

Contents

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1. Introduction

Air conditioning is defined as the process of controlling air properties (temperature, humidity, cleanliness and circulation) of a building interior using a refrigeration cycle [1]. The Japan Refrigeration and Air Conditioning Industry Association (JRAIA) has estimated that there was 94.5 million units of air conditioning systems sold in 2011 [2]. In Australia there is significant interest in installing air conditioning systems within residential and commercial buildings. In 2006, the estimated direct spending on refrigeration and heating, ventilation and air conditioning (HVACs) industry was A$15.96 billion [3]. According to [4], there are about 650,000 air conditioning units sold in Australia every year. The increase in air conditioning systems' sales in Australia is due to increased internal thermal load, variation of personal comfort level expectations and the significant variation in Australian climate.

The majority of buildings in Australia are cooled using mechanical vapour compressor air conditioning systems. According to [5], most of the air conditioning systems installed in Australian buildings are split systems which is accounts for 56% of total installed units, followed by ducted air conditioning at 21%, window types at 14% and evaporative at 9%.

The largest part of buildings' energy is consumed by heating, ventilation, and air conditioning (HVAC) systems which accounts for 68% of total energy consumed by building sectors followed by lighting at 19% and other purposes at 13%. George Wilkenfeld and Associates Pty Ltd. Policy and Planning Consultants [6] have reported that HVAC systems accounts for 30% of commercial sector total energy demand while residential air conditioning systems accounts for 38% of total energy demand by residential sector.

Currently most of Australia's electricity is produced using fossil fuels. According to [7], the world estimated crude oil and natural gas reserves will be depleted within the next 50 years. Moreover relying on fossil fuel energy recourses to generate electricity is affecting global warming directly due to fossil fuel burning's high negative impact on the environment. Consequently, global warming became the most common dilemma facing the world at the present time.

Traditionally, Australian Central Queensland regions have been associated with a steady subtropical climate. However, in the past 10 years a new climate patterns have been established which includes heat waves, droughts and cyclones. According to [8], in the region of Central Queensland the average annual temperature has increased 0.5 °C in the last 10 years and will reach up to 4.5 °C by the year 2070. So the trend of temperature increases will certainly increase space cooling cost and energy consumption.

Moreover Australian peak electricity load occurs in summer due to extensive usage of HVAC. The increase in air conditioning systems penetration rate is associated with high energy consumption. For example, in South Australia on a typical hot summer day, HVAC and refrigeration systems consume 46% of the state's total produced electricity [9]. HVACs' peak demand is the most important factor affecting capital investment in the Australian national electricity market. When most household and buildings' operators run air conditioning systems concurrently on a hot summer day, energy demands will lead to peak load at higher cost. Therefore, the electricity grid is increasingly facing the danger of overload that would cause essential service disruption and severe economic impact.

Institutional buildings contain different types of functional spaces. Lecture theatres, libraries and laboratories are the most important facilities within institutional buildings, and they are usually the largest air conditioned areas which host daily students and staff activity, machinery and instruments. In institutional buildings, HVACs' systems are a very important means to maintain a comfortable living space and to provide clean air to occupants. In addition, institutional buildings have a very high occupational density compared to other commercial buildings [10]. This high occupancy density generates a high heat gain as well as a high emission of body odours and water vapour. It is known that the human body has a constant temperature of 36–37 °C, independent of surrounding conditions and muscle activities. As a consequence, the human body has to transmit the excess heat to the environment by means of a different heat transfer mechanism. This excess heat consists of latent and sensible heat. The sensible heat is transferred by means of convection and radiation from the human body to its surroundings, while latent heat is transferred to surroundings by diffusion of vapour through skin and exhaled air [11].

The commonly measured source of air contaminations within institutional buildings are mould, microbiological contaminants, allergen pollutants, volatile organic compounds, carbon monoxide (CO) and carbon dioxide (CO_2) [12].

The balance between thermal comforts, indoor air quality and energy usage are building designers' main concern. Most of the research concerned with institutional buildings are dedicated to energy savings through building construction specifications, e.g. insulation and shadings [13] and HVACs' systems performance [14]. The ordinary practice to remove contaminants and pollutant from institutional buildings is through ventilation control with active heating and cooling systems which causes a major energy draw. Institutional building indoor environment (sound, temperature, humidity and indoor air quality) must be fiscally and environmentally balanced. However to maintain this necessary balance between indoor air quality and energy usage will force a large amount of fossil fuel burning to be simply wasted.

At the same time, most institutional buildings are using air conditioning economisers whose functions are based on using

more recycled air and using less air ventilation. However, using more recycled air will allow viruses, germs, dust and mould traffic. Due to Central Queensland region's high temperature and high humidity, fungus and mould growth have always been a problem. In high humidity climates, humidity is a major factor to be considered when designing HVAC for energy efficiency.

Fortunately Queensland (Australia) has one of the world's best solar resources. According to [15–17], Queensland has one of the highest solar energy concentrations in the world. The annual average global solar irradiance in Central Queensland region is 5.8 kWh/m^2/day [17]. Hence using solar energy to generate cooling is a very attractive concept, since in most of solar assisted air conditioning systems, solar heat is required to drive the cooling process, and this can be done by collecting solar radiation using solar collectors to convert it into thermal energy, this energy is then used to drive thermally driven cooling cycles such as desiccant, absorption and adsorption cycles [18].

Solar assisted air conditioning is an ideal option to achieve a high solar fraction that leads to a significant amount of energy savings and greenhouse gas emission avoidance. Solar assisted air conditioning systems are environmentally friendly by being constructed in a way that minimises the need for chlorofluorocarbons CFC, Hydro chlorofluorocarbons HCFC or Chlorofluorocarbons HFC refrigerants and by using low-grade thermal renewable energy. Additionally solar assisted air conditioning can be used either as stand-alone systems or with conventional HVAC, to save energy and to improve indoor air quality.

Most of the research and publications concerned with institutional buildings energy performance have considered energy savings via specific construction features such as thermal insulation, thermal mass, shading [19] and HVAC system efficiency and performance [20–23]. Solar assisted air cooling techniques have been investigated recently under various climatic conditions and different comfort level standards. Their energy savings, avoided greenhouse gas (GHG) emissions and its rule in affecting indoor air quality (IAQ) have been evaluated and analysed through a number of simulation and experimental studies. Zhao et al. [24] have designed, simulated and tested a solar cooling system in Alicante, Spain. The system which consists of 35 m^2 of flat plate collectors (FPC) achieved 29% of solar fraction (*SF*). There are some review articles available concerned with solar air conditioning technologies and their design options, mainly overseas [25–30]. There are also some research available on numerical evaluation which considered newly constructed solar cooling systems or suggested ones worldwide in order to determine their feasibility and to provide developers and operators with design and decision making tools [30–34]. Research on experimental evaluations of solar cooling technologies is also available. Lychnos and Davies [35] have proved experimentally the viability of solar cooling system of greenhouses in Athens, Greece. Lu et al. [36] have presented an experimental study to analyse four kinds of typical solar air conditioning systems with different sorption chillers and solar collectors in China. Li et al. [37] have developed a cooling system with 0.95 of COP in hot and humid climate conditions.

However, there are limited studies and research activities available in the literature that is concerned with Australian climates. Alizadeh [38] has tested a solar liquid desiccant cooling system under Brisbane climatic conditions. Goldsworthy and White [39] have analysed the performance of a combined solid desiccant and indirect evaporative cooler. White et al. [40] have modelled a solar desiccant cooling system in an office building without thermal backup in three Australian cities: Sydney, Melbourne and tropical Darwin. There are no research activities available on solar cooling systems in regional Australia. Consequently, achieving the important objective of reducing the state of Queensland's greenhouse gas emissions requires more relevant research activities, especially ones concerning solar energy as the state of Queensland's solar irradiance is reasonably abundant [41].

In this research paper, solar assisted air conditioning technology is reviewed. The paper first focused on Australian energy resources, conventional cooling techniques negative environment impact, solar systems and collectors and market available solar cooling techniques. The paper shall provide information, data, key measures and decision-making tools for designers, developers and operators about the best solar assisted air conditioning that can be operated under the Central Queensland subtropical harsh climate. This in turn will help to develop a model for a broad range of buildings such as hospitals, health care units, institutional buildings, museums, libraries and other vital commercial buildings.

2. Energy and energy resources in Australia

Energy is a very important factor in generating country wealth and strong economic development and growth. Fortunately, Australia has abundant fossil fuel energy resources and is the world's ninth largest energy producer. According to Australian government [42], Australia's power stations produced 261 billion kilowatt hours (TWh) of electricity in 2011. The main energy resources to produce electricity in Australia are black coal which represents 53.8% of total generation followed by brown coal, gas, renewable energy and oil at 22.5%, 15.9%, 6.8% and 1% respectively as shown in Fig. 1: [16]. Primary energy usage in Australia is predicted to increase across all Australian states over the next twenty years by 1.4% a year. Meanwhile energy production using renewable resources is predicted to increase by 19% at 2030 [43].

Australian electricity generation from renewable energy rose to 9.6% of the country's total electricity produced between 2010 and 2011 [44,45]. The total electricity produced by renewable energy

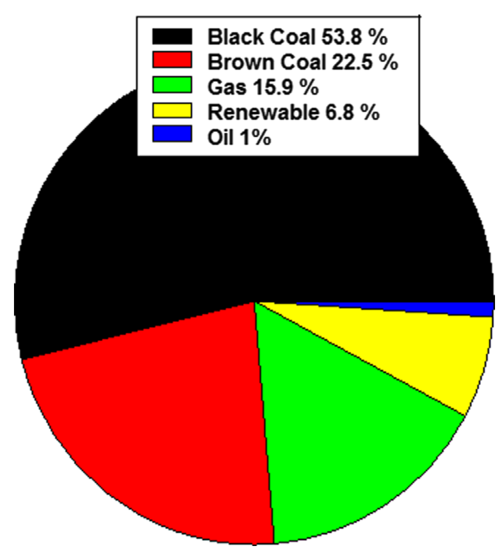

Fig. 1. Resources of Australian electricity generation.

Table 1
Annual renewable electricity generation.

Fuel source	Electricity (GWh/year)	Percentage
Hydro	19,685	67.2
Wind	6432	21.9
Bio-energy	2500	8.5
Solar energy	680	2.4
Marine	0.75	0.003
Geothermal	0.5	0.002

resources is 29,302 GWh as shown in Table 1. Hydro power generation accounts for 19,685 GWh, which represents 67.2% of total renewable energy generation followed by wind energy, bio-energy and solar energy, at 21.9%, 8.5% and 2.4% respectively as shown in Fig. 2.

Australian solar energy production is still small in scale compared to the leading countries in the world. The capability of Australian solar energy performance could be easily boosted as solar resources are abundant and supported with maps, data, scales, specification and local and federal government grants. In 2010, the Australian federal government presented what is known as renewable energy scales generation target to support renewable energy generation in the country. For this purpose Australian people are invited to take advantage of the growing renewable energy industry as well as of the strong economy, the easy access to grid, local and federal government intensive and grants, and organised legal services.

3. Energy and Australia's greenhouse gas emissions

According to [46], the population of Australia at the end of December 2011 was 22,734,362 people. From the year 2006 to 2011 the Australian population increased by 1,626,100 persons. This rapid population growth puts Australia as one of the most energy intensive countries in the world. Australia is a country with many conventional energy resources. Reliance on these resources has contributed to Australia having the highest greenhouse gas (GHG) emissions per capita in the developed world. In 2008 Australia produced nearly 1.5% of the total global greenhouse gas emissions which are equivalent to 576 million tonnes of CO_2 [47].

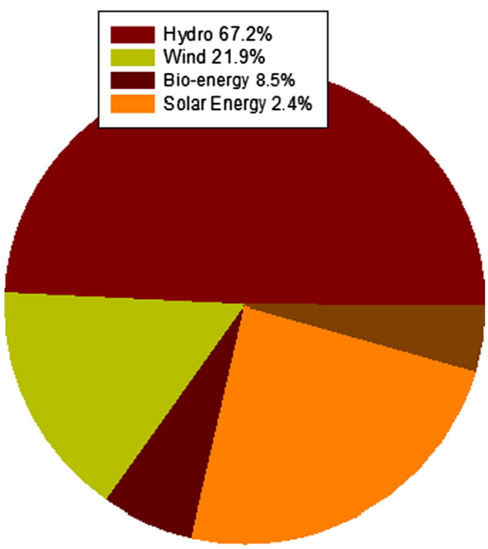

Fig. 2. Australian production of renewable energy.

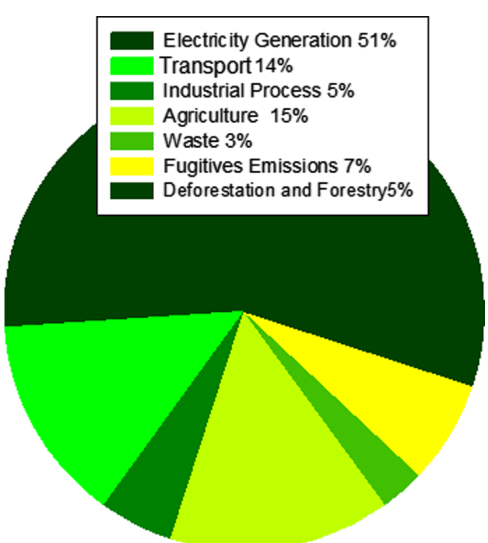

Fig. 3. Australia's emissions by sectors.

Over the past three decades Australian greenhouse gas emissions are continuing to build up as a result of human activities especially fossil fuel burning and decreases in carbon sinks as a result of forestry and loggers. The Australian Government's Department of Climate Change and Energy Efficiency [48] categorised greenhouse gas emissions into six sectors as shown in Fig. 3. Fig. 3 shows that electricity generation is the biggest greenhouse gas emissions contributor in Australia, accounting for 51% of the country total emissions. The second biggest greenhouse gas emissions contributor in Australia is agriculture at 15%, followed by transport, fugitives, forestry, industrial process and waste at 14%, 7%, 5%, 5% and 3% respectively.

There are different factors that determine future levels of energy usage, production and greenhouse gas emissions. Examples of these factors are population growth rates, economic performance, technology and living standards. Greenhouse gas emissions are projected to increase in Australia by 32% between 2010 and 2020 due to the country strong economy and the expansion of mineral and energy resources exports [48]. Consequently climate change is the outcome of greenhouse gases emissions, especially carbon dioxide (CO_2), which is building up in the atmosphere, causing the climate to change globally. The Intergovernmental Panel on Climate Change (IPCC) has stated that world temperatures will increase between 1.1 °C and 6.48 °C during the 21st century [49].

4. Energy consumption by Australian buildings

Buildings are considered as one of the most important infrastructure sectors in modern societies. However, commercial buildings consume a considerable amount of energy that has a direct impact on the environment. In fact this leads to significant greenhouse gas emissions and production of non-environmental materials. The building sector today accounts for 40% of the world's total primary energy consumption [101,50]. A similar scenario occurs here in Australia where the building sector consumes almost 40% of Australia's total produced electricity [50]. Additionally Australian commercial buildings account for 61% of total energy use by the buildings sector [51]. Moreover Australian commercial buildings' greenhouse gas emissions have grown by 87% between the year 1990 and 2008 [52]. The building sector is also responsible for nearly 27% of the country's total greenhouse gas emissions and that includes commercial buildings that accounted for 10% of the country's total greenhouse gas emissions. Fig. 4 shows commercial buildings' greenhouse gas emissions by buildings type. The retail industry is Australian commercial buildings biggest greenhouse gas emissions contributor at 29% followed by office building at 20% and then institutional buildings at 12% [53].

In Australia, commercial buildings have a poor energetic performing design especially those more than 20 years old. The reason behind that is climate variation, low insulation levels, glazing materials, the presence of air gaps and the usage of expensive cooling techniques [54]. Energy savings can be achieved through strict building regulations, better design, efficient appliances and the employment of renewable energy.

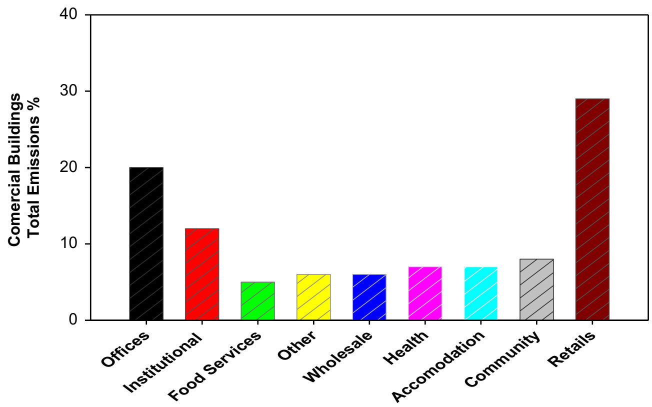

Fig. 4. Building gas emissions by sector.

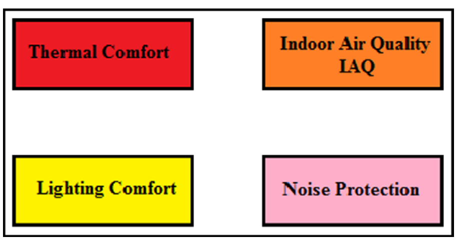

Fig. 5. Indoor environment quality groups.

Recently, Australian building sectors are entering a new epoch of change, with a focus to minimise operation cost and environmental impact by minimising energy, gas emissions and environmental footprint of commercial and residential buildings. Australian building regulations are the responsibility of the states' and territories' local governments. Each state and territory has its own building acts and regulations. In the last two decades Australian commercial building acts and regulations have addressed buildings' energy savings and greenhouse gas emissions. These regulations controlled commercial buildings' rapidly growing emissions in order to meet Australia's greenhouse gas emissions reduction target and to improve buildings comfort level standards as well as buildings' indoor air quality.

5. Indoor environment quality groups

In order to provide a suitable work environment for building occupants, the buildings' heating, ventilating and air conditioning (HVAC) systems must provide thermal comfort level and healthy living environment. HVACs' systems main task is to maintain indoor optimal comfort standard with minimal energy consumption and minimal negative impact on the environment. According to [55], the quality of the indoor environment is controlled by four requirements as shown in Fig. 5; they are thermal comfort, indoor air quality (IAQ), lighting comfort and noise protection.

5.1. Indoor thermal comfort

Indoor thermal comfort has been defined by [56,57] as the combination of indoor space environment and personal factors that will produce thermal environmental conditions acceptable to 80% or more of a building's occupants. This is due to an expected group of occupants' dissatisfaction with thermal environment during a building operation. Dissatisfaction with thermal environment is due to occupants' personal behaviours and difficulties in maintaining comfort level at all times. Maintaining thermal comfort standards in a building is the main object for HVACs' systems' design engineers. It is very important to maintain comfort level standards within a building or a space because thermal discomfort can lead to what is known as sick building syndrome (SBS) [58]. The most known symptoms of sick building syndrome are eyes irritations, nose dryness, sore throat, skin irritations and dryness and other general health problems [59].

5.2. Parameters of indoor thermal comfort

The combustion of nutrient materials and the transport of substances between the body cells produces heat. This procedure is known as the metabolism [60]. Thermal comfort can be maintained when the generated heat by human body (metabolism) is dissipated to the environment while keeping thermal symmetry with surroundings. The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) Standard 55 has identified the impacts of thermal environment on occupants' comfort in hot-humid climates and in a cold climate based on heat balance model of the human body assuming that thermal sensation is influenced by various environmental conditions (indoor air temperature, mean radiant temperature, humidity and air speed), and other personal factors (metabolic rate and clothing) [61].

Indoor air temperature is considered as the most important indicator of indoor thermal comfort. The importance of this indicator lies on the human body's capability to adapt to various seasonal conditions. The suitable indoor temperatures are between 20° and 22 °C in winter and 26° to 27 °C in summer when the ambient temperature is above 30 °C [55].

Mean radiant temperature is known as the mean temperature of the surfaces that environs an inhabited space. Mean radiant temperature has strong affects on radiating heat between human body and ambience. Auliciems and De Dear [62] stated that the difference between indoor air temperature and mean radiant temperature should not be greater than 2 °C. Therefore, a bright coloured or reflective external window blinds can be used to minimise the affect of mean radiant temperature.

Generally air humidity affects the latent heat transfer from human bodies to the environment and surroundings. The reason why air humidity in any conditioned building varies is because of different sources of water vapour such as human, plants and cooking. In the presence of high humidity the wetness of a human body will increase and this will prevent the evaporation of human skin sweats and respiration system vapours leading to discomfort. Moreover low relative humidity produces dryness, itching and annoying static electric sparks which lead to discomfort. According to [55,62] humidity should be 40 to 70% or the moisture content should not exceed 11.5 g/kg.

Air movement affects human body heat transfer by the means of convection and evaporation. The air velocity in a room controls the convective heat losses and evaporation of water, which the human body releases through skin and sweat glands. During cold ambient conditions human bodies feel uncomfortable with air velocities above 0.15 m/s, conversely in summer and hot days human bodies are comfortable with higher velocities up to 0.6 m/s

Another decider of thermal comfort is clothing. Clothing interferes with the human body's heat transfer to the environment. We can say that thermal comfort is highly dependent on the insulation effect of clothes on the wearer. The clothing affects to human body's indoor thermal comfort lies behind the fact that if the wearer is wearing too much clothes like personal protection equipment this might lead to a heat stress even in normal climatic conditions. At the same time if clothing does not provide enough insulation this may lead to cold injuries.

Finally the type of physical activities performed by human bodies and their metabolic rate is essential to assess indoor thermal comfort. People have different metabolic rates which

varies due to different human activities and environmental conditions [63]. Food and drink also control human metabolism and has an indirect influence on indoor thermal comfort.

5.3. Integrated indicators of indoor thermal comfort

Thermal comfort parameters can be evaluated using predicted main vote (*PMV*) indicator [13]. *PMV* is an agreed relative assessment scale of thermal comfort in the indoor environment. The values of *PMV* are arranged between −3 and +3. It can be said as −3 (cold), −2 (moderately cold), −1 (pleasantly cold), 0 (neutral), +1 (pleasantly warm), +2 (warm) and +3 (hot environment). When *PMV* equals zero it means a neutral environment, positive values of *PMV* means a warmer environment, and negative values of *PMV* means a colder environment [13,64]. The *PMV* values are established by a mathematical expression or based on measurements of thermal comfort parameters and by considering activities and clothing of the occupancies as given in [13,65]

$$PMV = e^{[Met] \times L} \tag{1}$$

where *Met* is metabolic rate in (Met), taking into account 1 Met = 58 W/m^2 and *L* is dry respiration heat loss.

The *PMV* formula applies when human bodies are exposed for a long period of time as well as maintaining constant conditions at a constant metabolic rate. The *PMV* can be related to percentage of not satisfied people, which tells us the percent of not satisfied people in an observed room.

6. Indoor air quality (AIQ)

Human beings as a condition of survival need a continuous supply of fresh and clean air. The need for air is relatively constant at 10–20 m^3 per a day [66]. Indoor air quality (IAQ) is defined as the essence or the nature of a conditioned air within a building or a structure. It is considered as the scenery of air that affects the building occupant's health and their well being. Janssen et al. [67] have defined an acceptable indoor air quality as indoor air where the air is free from any known contaminations at a harmful level. In addition, whether this air satisfies thermal comfort, normal concentration of respiratory gases (oxygen and carbon dioxide) and acceptable limit of air pollutants. Indoor air quality is a major concern for building designers, developers, operators, tenants and owners because human exposure to poor indoor air quality may cause a high health risk; like respiratory illness, fatigue, nausea and allergies. Furthermore indoor air quality affects occupants' comfort, production, job satisfaction and performance. In the past decade, there have been many debates among researchers, developers, business owners and public health officials about what governs an acceptable indoor air quality. The importance and motivations that lie behind indoor air quality control are health aspects due to human exposure to variety of indoor pollutants and high energy cost.

Presently, humans become alert for potential health hazards associated with poor indoor air quality and its negative impact on human production. This is due to gaseous or substances contaminants as well as biological and building particles released into indoor air and inadequate building ventilation. In addition poor indoor air quality can be exacerbated by the implementation of energy conservation strategies, the awareness of environmental issues associated with energy usage, sealed buildings, the wide spread of photocopiers and printers and other resources of air contaminators. IAQ depends on three important factors: the quality of outdoor air, the strength of contamination resources and its emissions including human bodies and ventilation adequacy [68]. Hence to maintain an acceptable IAQ, indoor spaces must receive a sufficient quantity of fresh and clean air that is free from chemical or microbiological contaminants.

6.1. Factors affecting indoor air quality

Poor indoor air quality is controlled by four factors that affect the serenity of air pollution and contamination. As shown in Fig. 6, these factors are: pollutant sources, physical building layout, building occupants and HVACs' systems.

- *Indoor air pollution sources*: Indoor air contamination sources are internal and external. Internal contamination sources are originated from buildings internal envelope whereas external contamination sources are originated from outdoor sources. The possible sources of contaminants and pollutants to indoor air are: biological contaminants, building materials and substances, tobacco and smoke, cleaning products and maintenance, combustion sources, HVAC systems, and outside sources [69].
- *Physical buildings' layout*: Physical building layout including sight, climate, building materials and furnishings, moisture, processes and activities within the building controls air pressure differentials and the way how indoor air moves inside a building as well as how much fresh outdoor air enters the building. Thus a sudden change of air patterns can affect contaminant concentrations in different spaces within a building thar have a direct impact on IAQ.
- *Buildings HVAC systems*: The main function of buildings HVAC systems is to change the indoor air property of an occupied space of a building in order to provide thermal comfort for occupants. Additionally buildings HVAC systems are designed to distribute outdoor fresh air throughout the building in order to meet ventilation needs of occupants. Consequently poorly designed or maintained ventilation systems will cause indoor air quality problems. In general, economic and environmental restrictions control buildings' ventilation system which has a direct impact on indoor air quality. For example in some cases buildings' operators reduce the amount of fresh air through the building in order to reduce the cost of HVAC systems operation.
- *Buildings' occupants*: Buildings' occupants are considered as a main source of contaminations. Buildings' occupants' contribution to contaminants and pollutants varies from one occupant to another as a result of different people having different metabolism rates and different activities such as cooking, washing, smoking, and body odour production. In some cases there are special groups of

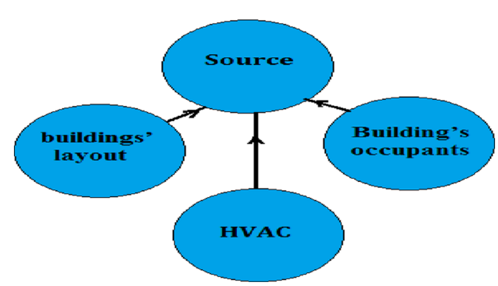

Fig. 6. Factors affecting air quality.

Table 2
Acceptable temperature and humidity ranges.

Measurement type	Winter (°C)	Summer (°C)
Dry bulb with 30% RH	21–25	23–26
Dry bulb with 50% RH	21–23.5	22–26
Maximum wet bulb	18	20

occupants that require different air purity standards and special conditioned air needs such as people with allergy, asthma, people with respiratory disease, people whose immune system is suppressed, people who require radiation therapy and people with contact lenses, etc [70].

6.2. Contribution conditions to IAQ and its control strategies

Indoor air pollution is ever-present, and has different forms, ranging from smoke emitted from solid fuel combustion to complex mixtures of volatile and semi-volatile compounds like materials used in modern buildings. Types of contaminants and pollutants can be different from one building to another depending on its nature and site such as the building's geographical position, the different materials which were used during its construction or operation and traffic volume around it. According to [71], the most common indoor pollutants are Carbone Dioxide (CO_2), Nitrous Oxide (N_2O), Carbone Monoxide (CO), Nitrogen Dioxide (NO_2), Sulphur Dioxide (SO_2), Ozone (O_3) and Radon. Fortunately many indoor air problems can be eliminated or decreased by adopting the following control strategies [70]:

- *Source control*: This strategy is considered as the most cost effective approach to eliminate or to reduce IAQ problems. Methods of source control strategy are:
  - Pollutions and contaminations sources elimination or reduction.
  - Pollutions and contaminations source cover or concealment.
  - Buildings' environment modifications e.g. indoor humidity and temperature control. An acceptable indoor temperature and indoor humidity ranges as advised by [56] are listed in Table 2.
- *Building's ventilation modifications*: This strategy is effective when buildings are under ventilated and when the source of contaminations or pollutions are unknown. Methods of ventilation modifications are:
  - Diluting contaminations and pollutions with outdoor fresh air.
  - Air pressure control to isolate pollutions or contaminations.
  - Increasing the flow of outdoor air.
- *Air cleaning process*: This strategy is the most effective way to mitigate IAQ problems especially when combined with either source control or ventilation. Moreover it is the only strategy that can be used when the contamination sources are external. Methods of air cleaning processes are:
  - Particulate filtration.
  - Electrostatic precipitation.
  - Negative ion generation.
  - Gas absorption.
- *Exposure control*: This strategy is a set of administrative tactics that can be used by buildings' managerial team and operators to tackle IAQ problems by controlling occupants' behaviours and activities. Examples of exposure control strategies are:
  - Scheduling contaminant-producing activities.
  - Relocating susceptible individuals.
  - Education and communication.

7. Humidity and mould growth

Air humidity is defined as the amount of water vapour in the air of a given space. The density of water vapour per unit volume is called absolute humidity. Humidity ratio is known as the mass of water vapour in g or kg to the mass of dry air in g or kg while relative humidity (RH) is defined as the ratio of an air water vapour partial pressure of air–vapour mixture to the saturated vapour pressure at a specific temperature times 100.

Fig. 7. Moulds in institutional buildings.

Humidity control is very important especially in subtropical and tropical climates as humidity variation can affect human comfort and can cause damage to assets e.g. library contents (books, computer, furniture etc). High humidity can cause condensation problems on cold surfaces, human heating and respiratory problems. High humidity affects human bodies' ability to sweat. Generally human bodies produce sweat to get rid of heat. When the surroundings are too humid, however, the air is saturated with moisture so that our sweat cannot evaporate off the skin. Due to water vapour condensation in building envelops with the presence of high temperature, mould will grow substantially causing diseases to human and animals, energy consumption and early deterioration for building materials as shown in Fig. 7. In situations where the indoor air is too dry, both humans and animals will experience symptoms of discomfort that span from dry skin to respiratory irritation.

The levels of humidity and the risk of high vapour condensation is always a concern for building designers operators in order to avoid implications because moderation of indoor humidity is a requirement for a healthy building. In order to minimise mould growth and to meet human comfort requirements, a reasonable relative humidity goal would be recommended to maintain the conditioned space in a range between 30 and 60%, as suggested by [56].

Fungus growth requires organic materials, moisture and high temperature. If one of those factors was eliminated, fungus growth could be mitigated [72]. In any conditioned space without active dehumidification and humidification the actual moisture level achieved in a ventilated building will depend highly on the outside air humidity, ventilation rate, and rate of moisture generation within the space. Consequently in subtropical climates during high humidity and temperature days, dehumidifiers must be in place to dehumidify warm and moist outdoor air in order to maintain space humidity levels below 60%.

8. Health aspects of poor indoor air quality and humidity

In some cases, building occupants with allergy, sinus problems and asthma may complain about comfort problems, symptoms they encountered and severe reactions similar to issues caused by indoor air pollution. Other issues building occupants' complain from could be caused by job stress, lights, monitor and screen glare, noise, vibration, work space environment, job dissatisfaction and other psychosocial factors [69]. These symptoms and issues are adversely affected by poor indoor air quality. In cases of continuous complaints by the building's occupants of health issues associated with working in the building, the building is called sick. The combination of ailments, syndromes and symptoms associated with a place of work or residence is known as Sick Building Syndrome (SBS) and Building Related Illness (BRI) [73].

- *Sick Building Syndrome* (*SBS*): The main known symptoms of SBS are headaches, dryness, irritation, sneezing and cough, dizziness and nausea or severe discomfort. Additionally building occupants encounter difficulty in focusing, exhaustion, and sensitivity to odours. Building occupants with SBS normally recover and feel relieved when they leave the infected building [74].
- *Building-Related Illness* (*BRI*): The most known symptoms of BRI are chest pain and tightness, fever and muscle ache due to occupant exposure to contaminated air. Building occupants with BRI are subjected to prolonged healing time after leaving infected buildings [70].

9. Energy conservation strategies within institutional buildings

HVAC systems are the biggest energy consumer within buildings. Energy use in institutional buildings depend on building envelop, HVAC system efficiency, fresh air required, lighting and their efficiency, internal loads, building operation and maintenance. Accordingly the operating costs of commercial buildings can be reduced if the lighting and HVAC systems are designed to be energy efficient. According to [75,76], energy conservation strategies can save up to 30% of the total energy used by the commercial building sector. Hence implementing certain strategies can reduce institutional buildings' energy demand:

1. *Operational management*: This process concerns rescheduling after hours activities and implementing a building management system which enables building operators to control full or partial shutdown of the building as well as control and regulate temperature in each space or zone to comply with ASHRAE comfort standards.
2. *Reduction of cooling loads* (*heat gain*): This can be achieved throughout a set of procedures including solar radiation control which leads to a reduction of heat gain throughout the building envelop. Solar radiation control can be controlled by implementing shading using planting and vegetation and by using light coloured exteriors walls.
3. *Buildings envelop modifications*: The most common techniques within building envelop modifications are the use of internal and external shading devices, double glazing, walls and roof insulations.
4. *Equipment modifications*: An example of this strategy is installing heat recovery wheels, natural and mechanical ventilation and installation of radiant terminals.
5. *Installation of passive and renewable energy cooling techniques*: these techniques are considered as free cooling techniques despite the fact they have high installation costs.

According to [77], the past techniques of energy savings strategies vary from one technique to another in terms of their installing cost and their energy savings as presented in Table 3.

The soaring price of fossil fuel and its associated negative impact on the environment means that we have to think deeply about using clean and renewable energy resources as an alternative. Solar energy is considered as a clean energy source because it is completely natural. Solar energy also does not affect the environment or cause a threat to Ecosystems compared to other energy resources. In addition it does not cost anything except the installation cost.

Table 3
Energy conservation strategies [77].

Methodology	Cost ranking	Energy savings (%)
Operational management		
After hours reschedule	Zero	0–10
Zones temperature control as in ASHRAE	Zero	4–8
Zones relative humidity control as in ASHRAE	Zero	4–8
Correct use of efficient electrical appliances	Zero	3–7
Control of external windows and shutters	Zero	0–5
Reduction of cooling loads		
Lighting control e.g. intensity and sensors	Low	4–6
Use of fluorescent lights	Low	4–6
Energy efficient appliances	Medium	10
Buildings envelop modifications		
The use of shading devices	Medium	2–19
The use of overhangs	High	2–18
The use of double glazing	High	4–7
The use of reflective film	Medium	3–11
Roof insulation	Medium	3–6
Equipment modifications		
Installation of a heat recovery unit Installation of efficient regulation systems	High	2–4
	High	2–8
Installation of radiant terminals	High	2–8
Installation of passive and renewable energy		
Solar cooling	High	30–80
Passive cooling	High	8–20

10. Solar energy

Solar energy is the energy produced by sun radiation. It is considered to be the most powerful, abundant, clean, environmental friendly and inexhaustible energy resource available to humans. The amount per hour of solar energy absorbed by the earth surface is enough to meet human energy needs for a year [78]. Humans have used the suns radiance, light and heat since ancient times through various techniques and means. In ancient times the sun has dried, preserved human's food and help to evaporate sea water to produce salt. It has been mentioned by Xenophon that in the year the Greeks (470–399 BC) used house and inhabitancy space orientation toward the sun in order to have cool houses in summer and warm ones in winter [79].

In general all renewable energy resources derive their energy from the sun except geothermal and atomic energy. For example wind energy is derived by temperature and pressure variation that is created by sun's affect. Hydro energy is a result of solar driven water cycle. Fossil fuels came as a result of drying process of organic matters by the sun's radiation millions of years ago.

Solar energy harvesting techniques are divided in two divisions: passive solar techniques and active solar techniques [80].

- *Passive harvesting techniques*: Examples of this technique are materials selections favourable for their thermal specifications, building designs with respect to natural air circulation and building oriented to the sun and sun light dispersing.
- *Active harvesting techniques*: Where solar collectors including electric photovoltaic panels and thermal collectors is used to convert solar radiation and heat into energy as shown in Fig. 8.
  - *Solar thermal collectors*: where solar radiations and heat is collected and used to produce heat. In other words it is defined as the conversion of solar radiation into thermal energy (heat). Solar thermal collectors are commonly used in hot water systems. It also can be used to heat different fluids such as air which can be used directly, for space heating, or to generate electricity.
  - *Solar photovoltaic* (*PV*) *modules*: where solar radiations are converted directly into electricity (Direct Current) using photovoltaic cells (PV).

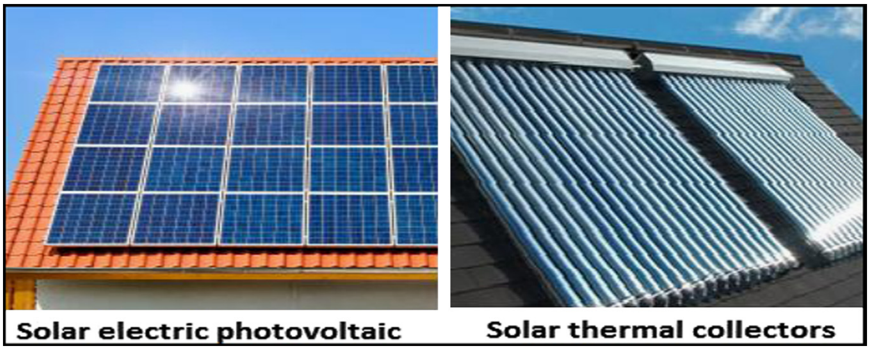

Fig. 8. Active solar energy techniques.

Solar energy received on the earth's surface is known as solar irradiance. In other words solar irradiance is the amount of solar energy incident on a given surface in a certain time. The most used unit to measure solar irradiance is W/m^2/d. According to [81] the total annual energy output from a solar system E in (KWh) can be calculated using

$$E = \eta_e \int A_C \times G \quad (2)$$

where η is energy conversion efficiency, A_c is solar panels surface area in (m²), G is the integrated solar irradiance over a year (W/m²).

However [82] have identified a key problem confronting a wider use of solar energy; this key problem is the substantial variation of spatial and temporal in solar radiation pattern. Hence assessment of solar energy resources in Australian regions requires high quality information and a comprehensive database. Solar resources' data base and information including solar integrated and detailed mapping and transmission resources should be made publicly available to potential developers. This will help solar development occur at the best possible locations.

10.1. Solar energy in Australia

Australian solar energy has a great potential to generate energy due to Australia's climate, which is considered as one of the sunniest in the world Australia has very large areas of inland desert with low percentage of cloud and rain [41] as shown in Figs. 9 and 10.

Meeting Australia's energy demands with solar energy is technically possible but there are some barriers preventing applications of solar energy being widespread. Those barriers are:

1. Solar energy requires big surface areas to collect solar irradiance.
2. The cost of solar energy production remains high compared to other production options.
3. Solar resources intermittency especially in rainy days.

According to the [45], more than A$5.2 billion was invested in renewable energy between 2010 and 2011, which was 60% higher than 2009 and 2010. Recently solar energy has become very popular for Australian homes and business owners due to local and federal government incentives that have made solar energy technology affordable. Most installation of solar panels was in the state of New South Wales (NSW) which is accounted for 32%, followed by Queensland, Victoria, Western Australia, South Australia, Australian Capital Territory, Tasmania and Northern Territory at 25%, 15%, 14%, 12%, 2%, 1% and 0.3% respectively as shown in Fig. 11 [84].

Solar thermal technologies are incepted and developed in Australia. In 2011, there were 704,459 solar hot water systems installed around Australia. This vast number puts this technology as the most common renewable energy resource among Australians [85]. Furthermore, there are other low temperature solar thermal applications used in Australia like solar crop and seed drying, solar ponds, solar air heating and solar assisted air conditioning [86].

The cost of solar energy can be reduced as a result of technology advances, manufacturing technique improvement, and increasing financial support throughout governments and energy agencies. In addition the improvement of solar collectors and thermals storage technologies will help overcome solar energy intermittency barriers.

10.2. Solar thermal collectors

Solar thermal collectors are the main and the most important component of any solar system. It can be said that solar collectors are a type of heat exchange that is designed to absorb and convert solar radiation into usable or storable forms of energy. The U.S. Department of Energy [87] has classified solar collectors into three types of collectors: low temperature collectors, medium temperature collectors and high temperature collectors as presented in Table 4 and described below.

- *Low temperature collectors*: The outlet temperature of these types of collectors normally ranges between 40 °C and 90 °C. The most common type of low temperature collectors is flat plate collectors (FPC). Low temperature collectors are used for processing heat e.g. to heat swimming pools and in HVAC systems. Normally collector's heat medium is water and air.
- *Medium temperature collectors*: The outlet temperature of this type of collector is 60 °C–250 °C. An example of medium temperature collectors is evacuated tube collectors (ETC). This technology is used on solar drying, solar cooking and distillation. Normally this type of collector's heat medium is also water and air.
- *High temperature collectors*: The outlet temperature of this type is more than 250 °C. An example of high temperature collectors are parabolic dish reflector (PDR). These types of collectors are used directly to produce electricity. An example of this collector's heat medium is liquid fluoride salts [88].

Market available collectors' fall into two categories as listed in Table 5: non-concentrated collectors where the collector area is the same as solar radiations' absorber area. The second is concentrated collectors where collectors have a concave reflecting surfaces or mirrors to intercept, magnifying and focus the sun's radiation to smaller receiving areas in order to increase radiation flux [79].

It is worthy to mention that on certain solar applications, sun tracking mechanisms are used to orients collectors toward the sun. In general sun trackers are used to minimise the angle of

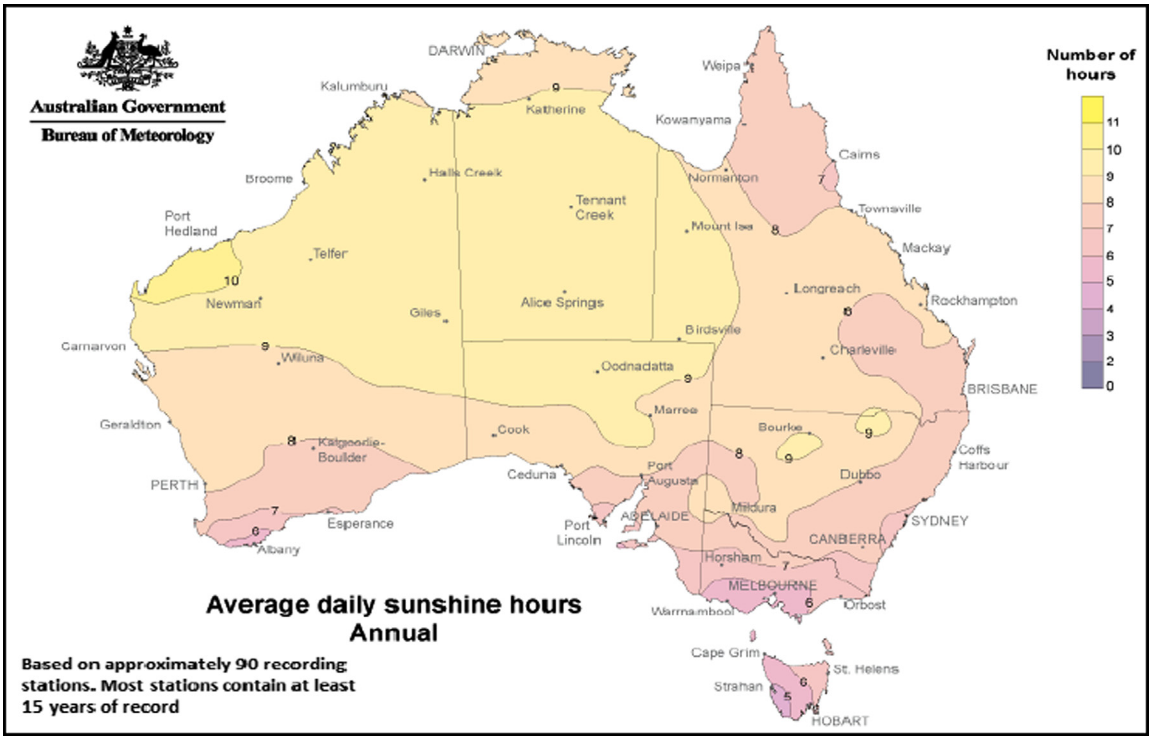

Fig. 9. Average annual and monthly sunshine duration [83].

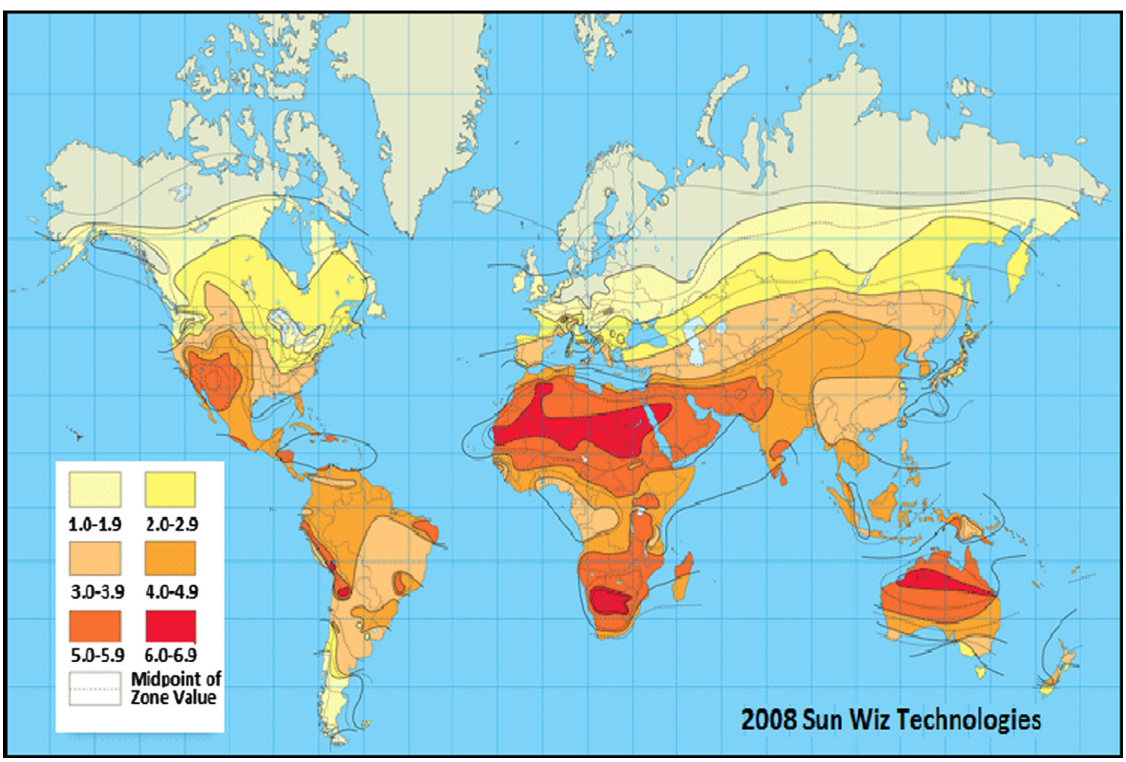

Fig. 10. Hours of sunlight per day, during the worst month of the year on an optimally tilted surface.

solar irradiance (incidence) between the incoming light and a solar collectors. Hence this technology (sun-tracking collectors) increases the amount of energy produced by the collectors.

In 2010, the operational capacity of solar thermal collector's around the globe was 195.8 GW that was produced by 279.7 million m^2 of solar collector's area. In 2011 the capacity of these collectors increased by 25% [89]. According to [90], China was the leading country in producing solar thermal energy at 117,600 MW/year followed by the United States at only 15,265 MW/year. The Australian solar thermal production in the year 2010 was positioned at fifth place, producing 5821 MW/year. Germany was in third place by producing 9604 MW/year followed by Turkey, Australia, Brazil, Japan, Austria and Greece by

producing 9323 MW/year, 5821 MW/year, 4278 MW/year, 3711 MW/year, 3191 MW/year and 2861 MW/year respectively as presented in Fig. 12.

10.3. Non-concentred collectors

These types of collectors collect solar irradiance without using magnifying or concentration mediums like mirrors. It is also able to generate heat at low and medium temperature scale (40–250 °C). Market available collectors that belong to this group of collectors are flat plate collectors, evacuated tube collectors and compound parabolic concentrators.

10.3.1. Flat plate collectors

Flat-plate collectors are the most common, cheapest and simplest type of solar thermal collector. These types of collectors were developed by Hottel and Whillier in the 1950s [91]. Flat plate collectors are shown in Fig. 13. They consist from the following:

The first part is the absorber: This part of the collector is a flat plate absorber of solar energy. The absorber consists of pipes network which has a direct contact with the absorbent background which is made from thin dark coloured metal sheet e.g. thermal polymers, aluminium and steels. Absorber plates are normally painted with special coatings, which is able to absorb and retain heat better than normal black paint.

Second part is the transparent cover (glazed): The weatherproof absorbent box is covered by a transparent cover (glass) and filled with air cavity between the surfaces to prevent heat dissipation and to minimise radiation losses. Third part is heat transport medium (fluid): A heat transport fluid is used in order to remove heat from the absorber and then transfer it to the end user or a storage facility. Examples of these fluids are air, antifreeze, glycol–water and water. Fourth part is the heat insulation box: The absorber system is fitted in a box that is insulated to prevent heat loss to the surroundings.

Based on the law of blackbody radiation the process starts by passing the sun light directly to the absorber plate through the glass cover, causing heat to the absorber. The heat is then removed by the transport fluids through the pipes network in the absorber box. Flat plat collectors normally are installed at a fixed solar collection angle.

This type of collector is commonly used to generate hot water for residential buildings, space heating and cooling and to heat swimming pools' water. The use of FPC in commercial buildings is limited to small businesses like a car wash, Laundromat and restaurant.

Table 5
Market available collectors [79].

Collectors category	Market available collectors	Absorber type
Non-concentrating collectors	Flat plate collector	Flat
	Evacuated tube collector	Flat
	Compound parabolic collector (CPC)	Tubular
Concentrating collectors	Linear Fresnel reflector (LFR)	Tubular
	Parabolic trough collector (PTC)	Tubular
	Cylindrical trough collector (CTC)	Tubular
	Parabolic dish reflector (PDR)	Point
	Central receivers collectors (CRC)	Point

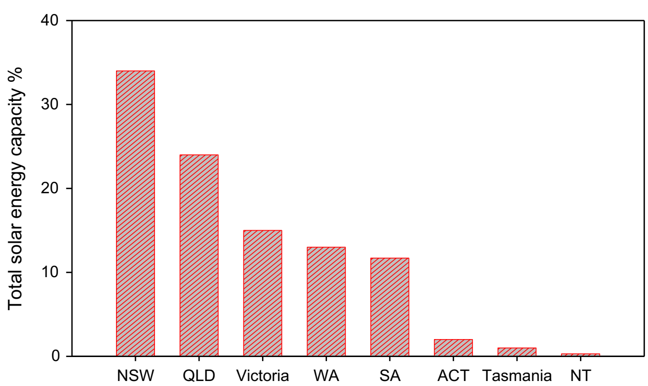

Fig. 11. Percentage of solar PV capacity by state [84].

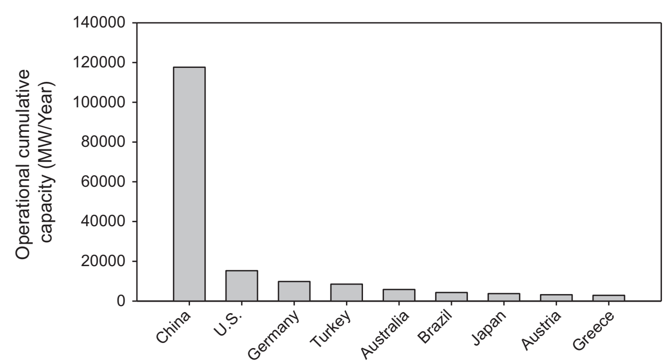

Fig. 12. Total capacity of solar thermal collectors in top leading countries by the end of 2010.

Table 4
Solar collectors' types.

Collectors type	Market available collectors	Concentration ratio	Fluid output temperature (°C)
Low temperature collectors	1. Flat plate collectors 2. Evacuated tube collectors	1–5	60–150
Medium temperature collectors	1. Evacuated tube collectors 2. Compound parabolic collector (CPC) 3. Parabolic through collectors	10–40	150–250
High temperature collectors	1. Parabolic through collectors 2. Parabolic dish collectors 3. Central receivers collectors 4. Heliostat field collector (HFC)	200–3000	250–1000

10.3.2. Evacuated tube collectors

Unlike a flat plate collector, evacuated tube collectors consist of an array of parallel evacuated heat pipe tubes (EHPT) which are connected to the top header pipe or a heat exchanger manifold as shown in Fig. 14. Each heat tube is composed of a metal heat pipe that is connected to a dark coloured absorber plate. Absorber and the heat pipes are normally made from copper, due to its superior thermal conductivity. Both components setup are surrounded by glass tube to prevent convection and conduction heat loss to surroundings, where the space between the tube and the absorber is evacuated [93,94].

On ETC, the heat process is achieved by transferring heat into the header tube (heat exchanger manifold). The sealed metal heat pipes contain a small amount of fluids below atmospheric pressure. The low pressure fluids evaporate causing the hot gas to rise up in the heat pipes by convection. Then the condensed fluid falls down the heat pipe by gravity, so the process starts again. Due to evacuated tube collectors tubular design it is capable of collecting sun energy from different angles. Evacuated tube collectors (ETC) are the most efficient solar thermal collectors. This type of collectors is commonly used in cooking, commercial buildings' water heating, solar cooling technologies (excludes desiccant) and electric power generation.

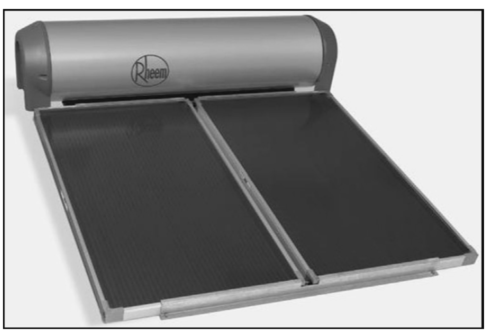

Fig. 13. Flat plate collectors (FPC), [92].

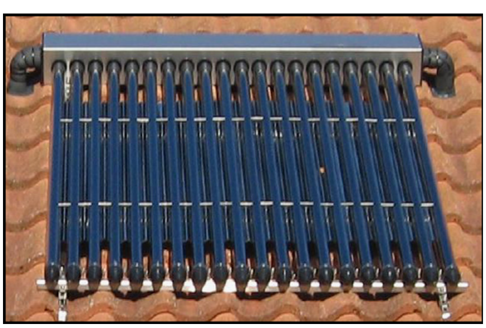

Fig. 14. Evacuated tube collectors (ETC), [95].

Fig. 15. Solar air collector.

10.3.3. Solar air collectors

Solar air heat collectors are a type of collectors where sun radiations are harvested and used to heat air directly. It is considered as the most cost effective solar energy technique [96]. This technology can be classified into two categories: glazed and unglazed collectors. Glazed collectors are transparent (covered) collectors that have a top sheet and an insulated side and back panels to minimise heat loss to the environment. In glazed collectors' air passes along the front or back of the absorber plate gaining heat directly from it. Unglazed collectors as shown in Fig. 15 are an air heating system that consists of a metal plate where air passes through while gaining heat from the absorber.

According to [96], the most common market available collectors that belong to this category are transpired solar air collectors. Solar heat air collectors can be used directly for various applications or may be stored for later use. The most common applications for air glazed collectors are spaces heating and drying and it is also widely used in agriculture industry in crops drying.

However solar air heat collectors have two known disadvantages: low thermal capacity of air and low absorber to air heat transfer coefficient [97].

10.4. Concentrated solar collectors

As mentioned earlier concentrated solar collectors intercept sun direct radiation over a large area of magnifying mirrors or lenses and focus it out into a small absorber area. These types of collectors can provide a higher temperature than non-concentred collectors, since the absorption area is smaller. Most of concentrated solar collectors require sun-tracking devices to orient the collectors toward the sun constantly and to keep the absorber at focus point. Concentred solar collectors are able to generate heat at medium and high scale temperatures ranging from 250 °C to 1000 °C. Besides electricity production, concentrated solar collectors systems can be used in solar air conditioning and high draw hot water facilities. Concentration solar collectors that belong to this group of collectors are parabolic trough dish Stirling, concentrating linear Fresnel reflector and solar power tower.

10.4.1. Parabolic trough collectors

Parabolic trough collectors are a type of solar energy collectors made from coated silver or polished aluminium (mirrors) which is shaped like the letter U as shown in Fig. 16. They constructed and installed to form long parabolic mirrors with a flask tube (Dewar) running on its length at a focal point. Sometimes a transparent glass tube envelops the receiver tube to reduce heat loss. The trough collectors can be oriented on a north south axis and have a sun tracking devices to rotate it in order to harvest the maximum

Fig. 16. Parabolic trough collectors [99].

possible sun irradiance. Otherwise it is can also be oriented on an east–west axis with no need for a sun tracking device as it needs to be aligned seasonally at less efficiency [98]. Heat process in parabolic trough collectors is achieved by transferring heat from the absorber to the heat transport fluid (oil). Then the heated oil temperature increases to near 400 °C which can be used to generate steam. Parabolic trough collectors are commonly used to produce electricity and in some cases it can be used in commercial buildings' solar cooling technologies (excludes desiccant).

The selection of suitable solar collectors depends on the climatic conditions, load requirements, costs, and output temperature. In HVAC applications solar collectors required temperature ranges from 60 to 250 °C which is considered as small and medium temperature scale collectors and on most cases there is no need for sun tracking devices (Stationed). Consequently high temperature collectors are not considered in this study.

11. Conventional refrigeration

Refrigeration is a process where work is done to remove heat from one location to another. The work in most cases is mechanical and in special cases is heat, electricity or other means. Refrigeration has many applications including domestic and commercial freezers, refrigerators and air cooling systems. Refrigeration process is classified into two classifications: non cyclic and cyclic [100].

Non cyclic refrigeration is accomplished based on total loss refrigeration principle e.g. melting ice or sublimations of frozen carbon dioxide. By melting ice, heat is transferred by convection from the warmer air inside a refrigerated space to the ice which absorbs 333.55 kJ/kg of heat, making the refrigerated space cooler than ambient. Moreover frozen ice carbon dioxide sublimes directly from solid to vapour state by absorbing heat from ambient environment at minus 78.5 °C which makes the refrigerated space below ambient temperature during sublimation. Non cyclic refrigeration is used on small scale applications e.g. portable coolers, workshops and laboratories.

Cyclic refrigeration operates using compression and expansion of refrigerant e.g. Chlorofluorocarbons (CFC) and Hydro chlorofluorocarbons (HCFC). Heat is removed from a cooled space and rejected to a higher temperature sink by means of work and inverse work that is carried out by a refrigerant. Naturally heat flows from hot to cold. In cyclic refrigeration, work is applied to the refrigerant that absorbs and rejects heat as the refrigerant circulates through a refrigerator and pumps it from a low temperature heat source to higher temperature heat sink. Cyclic refrigeration is divided in two classifications: Gas cycle and vapour compression cycle refrigeration systems.

Currently the dominant refrigeration and cooling systems worldwide are electrically driven vapour compression machines. According to [101], vapour compression systems market share accounts for 90% of market available refrigeration and cooling systems around the world.

11.1. Gas cycle refrigeration

Gas cycle refrigeration units consist of centrifugal compressor, primary air-to-air heat exchangers, secondary air-to-air heat exchangers, expansion turbine and fan as shown in Fig. 17.

Gas cycle refrigeration systems use gas such as air as a working fluid. This gas is compressed and then expanded but does not change phase, similar to Freon cycle. Because there are no condensation and evaporation, this cycle uses hot and cold gas to gas heat exchangers. However this type of refrigeration is less efficient than vapour compression cycle systems due to the large amount of gas required with large mass flow rate for the same cooling load. Therefore this type of cooling is normally used by jet aircrafts due to readily available compressed air that is produced by the engines' compressor sections. Refrigeration process is achieved by directing the aircraft engine exhaust air through the primary air to air heat exchanger where external air is used as a coolant. Then the cooled air is compressed and heated to near 250 °C using a centrifugal compressor. After that it is sent to the second air to air heat exchanger which also uses external air as a coolant to lower compressor entering air temperature further. Later the compressed cooled air is expanded by passing it through expansion turbine which extracts work from engine exhaust air. Consequently the cooled air temperature is below external air temperature which is ranging from −20 and −30 °C. Finally the cooled air is mixed in a mixing chamber with a small amount of uncooled engine bleed air to warm it to a desired comfort temperature and then the air is directed into the cabin or to electronic equipment.

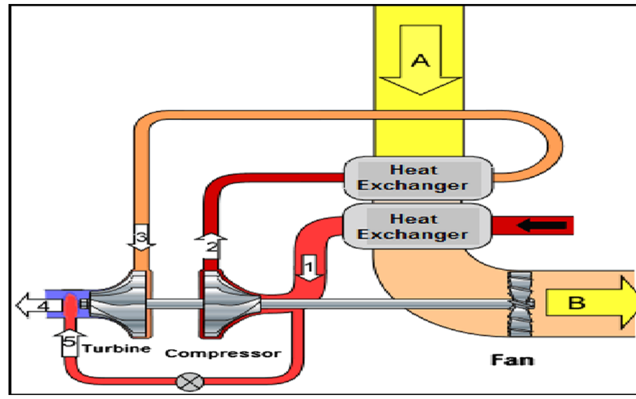

Fig. 17. Air cycle refrigeration machine [102].

11.2. Vapour compression refrigeration

Vapour compression cooling systems are the most used technology in the air conditioning and refrigeration industry [7]. Conventional vapour compression cooling systems use sealed circulating refrigerant e.g. chlorofluorocarbons (CFC) and Hydro chlorofluorocarbons (HCFC) to absorb and remove heat from a cooled space and reject heat elsewhere. Vapour compression refrigeration and cooling systems have four basic components: evaporator, compressor, condenser and expansion valve (throttle valve).

The cooling process as shown in Fig. 18, starts with stage 1 by entering (the compressor) where the circulating refrigerant enters the compressor as a saturated vapour and compressed to higher pressure and higher temperature (stage 2) to form a superheated vapour. During stage 3 (the condenser) the superheated vapour enters the condenser and has its heat removed from it, causing it to condensed back into a liquid phase (saturated liquid) using cooling water or cooling air where heat is rejected from the system. Afterwards the saturated liquid from the condenser is routed through (stage 4) the expansion valve, allowing its pressure and temperature to drop considerably. On the other hand, the refrigerant temperature in the evaporator (stage 5) is less than the cooled space temperature. As a result of that, the heat is absorbed by the refrigerant causing it to boil and then change phase from liquid or near-liquid to vapour again. Meanwhile, the circulating air is cooled and then lowering the temperature of the cooled space to desired temperature. Then to complete the cooling cycle,

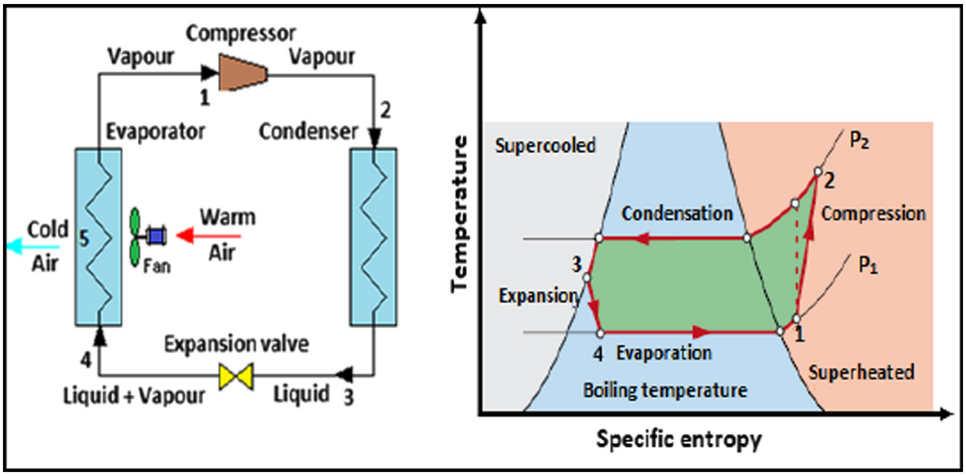

Fig. 18. Vapour-compression refrigeration system [103].

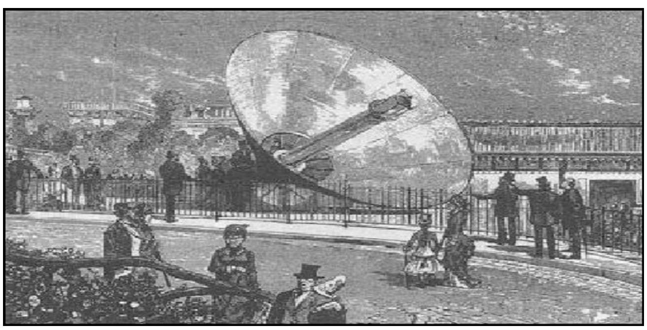

Fig. 19. Block of ice solar generation 1878 by Mouchout [107].

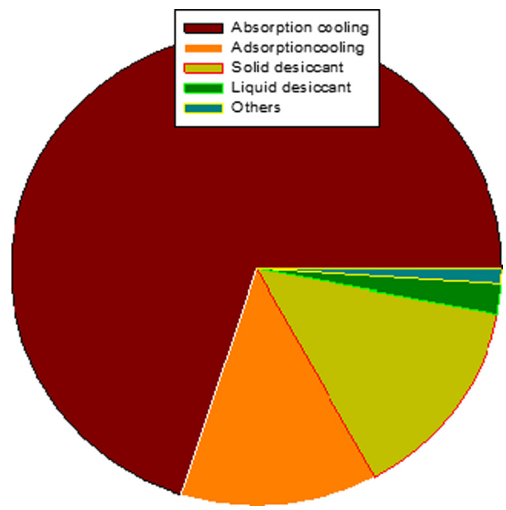

Fig. 20. Solar cooling technologies by categories [108].

the refrigerant passes to the compressor to repeat the whole cycle over again.

Vapour compression cycle is characterised by its low mass flow rate, high coefficient of performance (*COP*), low cold plate temperatures and the ability to transport heat away from its source.

12. Solar cooling technologies

The idea of air conditioning started in 1848 when Johne Gorrie constructed an ice making machine with a fan to blow air on the ice in order to cool down the hospital rooms where malaria and yellow fever patients were treated [104]. In 1881, the U.S. naval engineers constructed an expensive cooling system for the dying president of the U.S. James Garfield that consisted of a box containing a cloth saturated with melted ice and a fan blew hot air overhead. This mechanism was able to reduce the room temperature by nearly 11 °C. The invention was high cost due to the large amount of melted ice used in the process. It was estimated that the system consumed half a million pounds of ice in two months. Willis Carrier made a similar system to today's air conditioning system in 1902. The cooling system was named the Apparatus for Treating Air [105].

Auguste Mouchout developed a steam engine driven by a solar parabolic collector to produce a block of ice 1878 for the Paris Exhibition. The invention consisted of a mirror over 3.96 m in diameter and 79.5 litters boiler as shown in Fig. 19 [106].

According to [18], deployment of solar cooling technologies in indoor thermal comfort took place during the 80s of the last century especially in the United States of America and Japan. Since then many activities in this field have been started. These activities include researches and demonstration projects in many countries around the globe. The surge of this technology in recent years was due to the combination of environmental consciousness and soaring prices of fossil fuels. Compared to conventional cooling systems, there are a small numbers of solar HVAC systems installed around the world. The majority of these projects are in Europe, Middle East, Australia and the Mediterranean islands. It has been reported that in 2011 there were about 750 solar assisted air cooling systems installed worldwide including small cooling capacity 5 kW and high cooling capacity up to 1470 kW [2].

The majority of these installed solar cooling systems are absorption cooling systems which accounts for 70% of total installed systems followed by solid desiccant systems, adsorption systems, liquid desiccant systems and others at 14%, 13%, 2% and 1% respectively as shown in Fig. 20. It is worthy to mention that the leader of the solar assisted air conditioning industry worldwide is the International Energy Agency (IEA). A multinational body established the organisation in 1974 in order to improve the performance of several energy technologies. Hence the Solar Heating and Cooling Program was one of the first programs that the organisation investigated and researched.

Henning [18] has classified solar cooling systems into two categories: solar electric process using solar photovoltaic and solar thermal process using solar thermal collectors.

12.1. Solar electric (photovoltaic) cooling systems

This type of solar cooling is the conventional cooling systems e.g. vapour compression cooling system powered by photovoltaic (PV) cells as shown in Fig. 21. In general PV panels provide power for any type of electrically driven cooling system. Furthermore, it is mostly implemented with compressors based cooling systems which is considered the least efficient type of electrical cooling system [109]. Solar photovoltaic cooling techniques are suitable for domestic and small commercial cooling applications or for those applications requiring cooling capacity less than 5 kWh. One of the main advantages of using photovoltaic for cooling and refrigeration is the simplicity of the cooling system installation. Solar electric cooling and refrigeration systems are designed and fitted on independent operation and packaged containers [110].

Thermoelectric coolers which are made of semiconductors are another sort of cooling and refrigeration can be powered by photovoltaic. Thermoelectric coolers are suitable for applications with low cooling capacity (under 25 W) [112]. As these types of coolers have no moving parts or refrigerants and can be made very small and insensitive to motion or tilting, it is suitable to be used in electronic chips cooling and in portable refrigerators similar to ones used in space applications.

Moreover Stirling refrigerators can be powered by solar PV panels to provide cooling. However it is very difficult to develop an efficient Stirling cooler. The major problems of these types of coolers are their low *COP* and the limited cooling capacity due to the poor heat transfer between the working fluids and surroundings [113].

Electrically driven thermo acoustic cooling systems are another technology that can be powered by PV panels. In this technology cooling is achieved by pressure changes in acoustic waves that lead to transfer heat between two channels at different temperatures. A thermo acoustic cooling system has no moving parts and low cooling capacity. Hence no machine has been reported with a suitably large capacity for air conditioning. In addition, the major disadvantages of this systems is their low efficiencies [114].

There are several research studies concerning the above cooling technologies that are worth mentioning. Ewert et al. [115] have investigated a small cooling capacity of a 100 W with piston free Stirling cooler. Berchowitz et al. [116] Kribus [113] have investigated a similar system in term of its coefficient of performance (*COP*). Poese et al. [117] have tested the performance of a refrigeration system with a cooling capacity of 119 W designed for ice cream cabinet. Shir et al. [118] have researched Magnetic cooling technology.

However, due to photovoltaic cells high cost, low efficiency and subsequently high price of PV electricity conversion, these systems are not cost effective.

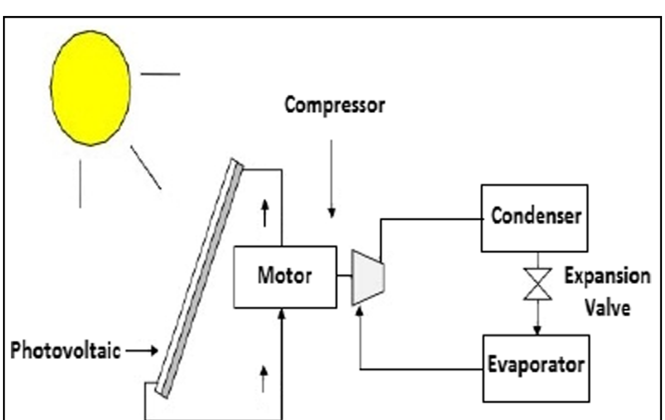

Fig. 21. PV cooling process [111].

12.2. Solar thermally driven cooling systems

In thermally driven solar cooling systems, solar heat which is produced by solar thermal collectors is used to drive the cooling process. Thermally driven cooling systems have been used for many years, but they have been driven by industrial processes' waste heat. Lately, demonstration projects worldwide have proved the potential of using solar thermal energy to drive the cooling process. Normally solar thermal cooling systems are available on a very large cooling capacity. Due to solar thermal collectors decreasing costs and the increase in their efficiency, the challenge is to develop smaller cooling systems (under 10 kWh) as well as to improve system performance. Solar thermal cooling system consists of solar collectors, hot water storage, pipes, pumps, and a thermally driven cooling machine. The cooling application driving temperature is normally below 250 °C. The most commonly used solar collectors are flat plate collectors, evacuated tube collectors and parabolic trough collectors. According to [7,18], solar thermally driven cooling systems are classified into two groups: thermo mechanical process group and heat transformation process group.

12.2.1. Solar thermo mechanical process technologies

The main principle of solar thermo mechanical cooling technology is that a heat engine converts solar thermal energy (heat) to mechanical work, which drives a conventional cooling system such as vapour compression cooling system. A schematic diagram of such a cooling system is shown in Fig. 22.

In this type of cooling system, thermal solar collectors convert sun radiation into heat. This heat is then directed into a heat engine to produce mechanical work. Then the mechanical work drives a vapour compressor to remove heat from a conditioned space.

The most known cooling applications belonging to solar thermo mechanical cooling technology are Rankine cycle based cooling systems and Ejector based cooling systems (steam ejector). Market available solar thermo mechanical cooling systems are available in big cooling capacities. Thus such a system is suitable for large air conditioning applications.

12.2.2. Rankine cooling systems

The Rankine cycle is the fundamental thermodynamic foundation of the steam engine. The working principle of Rankine cooling cycle is schematically shown in Fig. 23; Rankine cooling cycle systems convert the heat provided by the solar thermal collectors into work. It utilises the turbine generated power to drive a vapour compressor cooling system [119]. In short it is the combination between Rankine power cycle and a conventional vapour compression cooling cycle.

Rankine cooling systems have a high coefficient of performance (*COP*). It has been reported by [7] that the Rankine cooling system

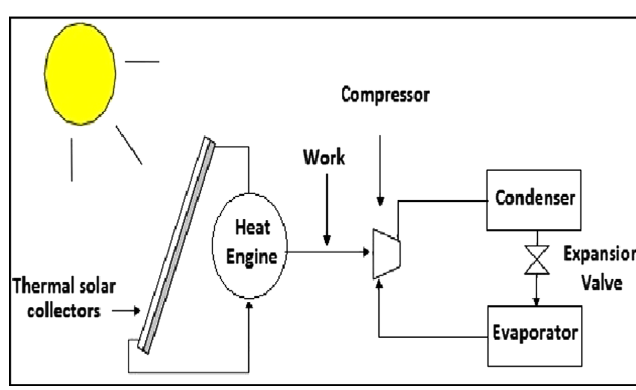

Fig. 22. Solar thermo-mechanical cooling system [111].

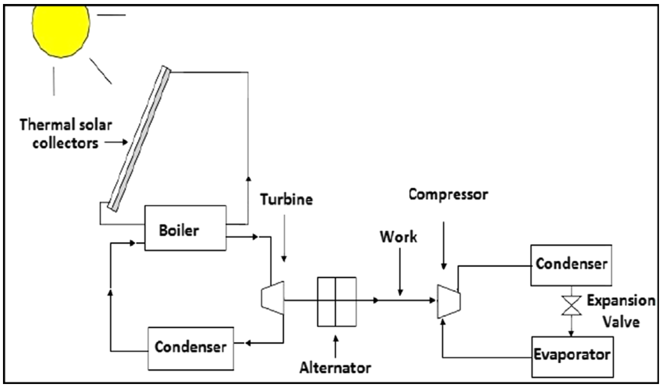

Fig. 23. Solar Rankine cooling cycle.

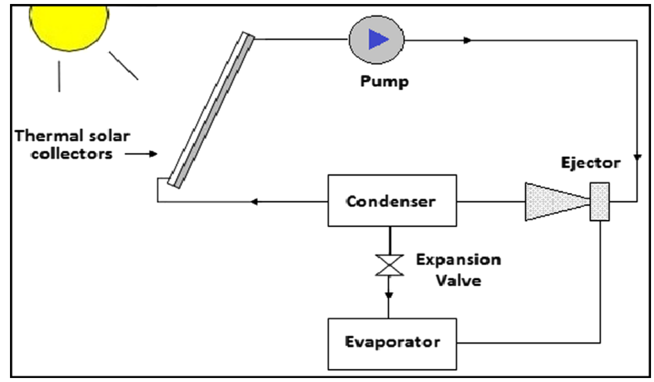

Fig. 24. Solar ejector cooling cycle.

COP is the same as a vapour compression cycle, whereas the efficiency of Rankine power cycle is low and has a direct relationship to the cooled space temperatures, sink temperature and the temperature of solar heated fluid. The overall system performance can be boosted using high efficiency solar collectors.

According to [111] solar Rankine cooling systems and refrigeration have been extensively investigated since 1970. In 1975 [120] designed a water cooled organic Rankine cycle. The system achieved an 11.5% efficiency using 101.7 °C water steam temperature. In 1980 [121] suggested using different fluids other than water which was halocarbon compounds (R-11, R-113 and R-114) and the fluorinated compounds (FC-75 and FC-88) for safety reasons. Due to the system working fluids environmental issues, research activities put on hold until interest gained momentum in the 21st century.

In the recent years there is much research concerning Rankine cooling cycles. Bao et al. [122] have researched a cascade low temperature solar Rankine cooling cycle using Zeotropic mixture Isopentane (R245fa) as working fluids. Quoilin et al. [123] have proposed a design of a solar organic Rankine cycle suitable for Lesotho for rural electrification purposes. Wang et al. [124] experimentally investigated the performance of a low-temperature solar recuperative Rankine cycle system using working fluid R245fa. Vélez et al. [125] have investigated the technical and economic aspects of a Rankine cycle.

12.2.3. Ejector cooling systems

Ejector cooling systems are similar to conventional vapour compressor based cooling systems. The difference is that, in ejector cooling systems, the compressor is replaced with the ejector which is considered as a thermally driven compressor that operates in a heat pump cooling cycle [126]. According to [127], ejectors have been known prior to 1900. In 1901 ejector cooling cycle was introduced by Le Blanc and Parsons when they successfully produced a refrigeration cycle using an ejector powered by heat energy [128]. Ejector systems use heat produced by thermal solar instead of electricity to compress refrigerant without using any moving parts. Hence the compression effect is vibration free. Besides the vibration free advantage, ejector based cooling systems are characterised by their simplicity, low operating and low installation cost and their capability of producing cooling from renewable energy resources. However the system's biggest disadvantage is its low *COP* which is usually under 0.4 [129].

Solar ejector based cooling system consists of three circulating loops as shown in Fig. 24 [126,130]; the solar system phase, ejector power phase and ejector cooling phase. The solar phase consists of a pump, solar collectors and a generator (heat exchanger) to transfer heat to the ejector phase. In the solar phase, solar collectors heat the working fluid which is normally water to near 95 °C. Then the heated water leaves the solar collectors to circulate through the generator. The generator transfers heat to the working fluid of the ejector power phase without mixing the two different working fluids flows, which results in a high pressure and temperature vapour. An example of the ejector power phase working fluid is halocarbon compounds (Dichlorofluoroethane-R141b). The high pressure refrigerant vapour passes the primary nozzle of the ejector. Then stream accelerates and expands through the ejector to create a low pressure area. This partial vacuum created by the ejector part transferred refrigerant vapour from the evaporator. The evaporator pressure is then reduced and the refrigerant boils causing a low pressure and temperature medium [129].

Over the years there are several research activities concerning solar Ejector cooling systems in order to improve system performance using multi stages ejector or hybrid systems. The first theoretical prediction model was carried out by [131]. In the last decade solar ejector based cooling systems have been investigated extensively due to their simplicity of construction. Ersoy et al. [132] have numerically investigated the performance of a solar ejector cooling system under the Turkey climate. Sarkar [133] has provided an overview concerning two-phase ejector cooling system's geometry, operation and modelling. Cardemil and Colle [134] have researched a vapour ejector performance taking into account ideal and real gas fluids. In Australia, the Australian National University [127] are investigating a high performance solar ejector cooling system.

12.3. Heat transformation process cooling technologies

To reduce the primary energy consumption by cooling systems, solar thermal heat transformation cooling technologies should be considered. In this type of cooling technologies, the produced heat by solar collectors is converted directly into cooling using thermally driven air conditioning systems. These systems function based on a physical phenomenon of sorption (sorption process). In general Sorption refrigeration uses a chemical attraction between two substances to produce refrigeration effect.

The main difference between heat transformation process cooling technologies and conventional compression cooling systems is the drive energy. In conventional compression cooling systems the drive energy is electrical or mechanical while in heat transformation process cooling technologies the drive energy is thermal energy that can easily be supplied by renewable energy. Hence solar energy is the most available heat source for solar heat transformation process cooling technologies. In addition, this technology is categorised based on the way they control and deliver cooling into conditioned space. Accordingly, solar assisted air conditioning systems are classified into two types: closed systems and open systems.

12.3.1. Closed cycle cooling systems

In closed cycles cooling systems, chillers produce chilled water which is either used in air handling units or in decentralised room installations, e.g. fan coils to supply a space with cooled and dehumidified air. Closed cycle cooling systems are an increasingly common technique in commercial buildings in order to provide cooled air. Market available thermally driven chillers are: absorption and adsorption chillers.

12.3.1.1. Absorption cooling systems. Absorption cooling systems have a great potential to save energy and to minimise buildings' gas emissions. It can be used widely in all kinds of newly constructed or existing older buildings. The absorption cooling systems are mature but it is considered as the most used system in solar cooling and refrigeration applications. Absorption cooling machines generates cold water from hot water which can be generated by solar thermal collectors.

The thermodynamic cycle of absorption chillers is normally driven by a heat source. In short the main concept behind the function of absorption cycle is based on chemical attraction between two working fluids: the refrigerant and the absorbent. The refrigerant has a lower vapour pressure than the absorbent. Up to date there are two known working fluids used within absorption chillers: lithium bromide (LiBr) pair and ammonia (NH_3) pair. Both working fluids have their advantages and disadvantages as presented in Table 6. In lithium bromide (LiBr) pair, LiBr is used as the absorbent while water is the refrigerant. In ammonia (NH_3) pair, NH_3 is the refrigerant and water is the absorbent. Chillers using LiBr pair normally produce water temperature between 5 and 8 °C while chillers using NH_3 pair are used in special industrial refrigeration and other applications required for water temperature under 5 °C [135,136].

The function of the two types of chillers is similar to a conventional cooling system where the role of a mechanical compressor is replaced by a thermal compressor which consists of an absorber, a generator, a pump, a condenser, an evaporator and a circulating valve as schematically shown in Fig. 25. The absorption cooling cycle starts in the evaporator where the refrigerant evaporates in a low partial pressure environment to the absorber; the evaporation of the refrigerant causes heat to be extracted from surroundings and thus cool down the chilled water. Then the gaseous refrigerant is absorbed into the other liquid (the absorbent) which causes its partial pressure to be reduced in the evaporator and allowing more liquid to evaporate. The diluted liquid of the refrigerant and the absorbent materials is pumped to the generator where the mixture liquid is heated using a heat source (solar and a backup heater) causing the refrigerant to evaporate and then condense on the condenser (heat exchanger) to refill the supply of liquid refrigerant in the evaporator through a circulation valve. In absorption based cooling systems, the liquid circulating pump and the backup heater are operated by electricity. However circulation pumps' energy consumption is too small compared to conventional cooling systems electricity consumption [138].

Table 6
Absorption chillers working pairs [137].

Working pair	Advantages	Disadvantages
$LiBr/H_2O$	Have a high COP a maximum of 1.2 Low operation pressure Non toxic	Corrosive Need a vacuum Crystallisation possibility
H_2O/NH_3	Evaporate below 0 °C Inexpensive	Toxic Need high working pressure Need rectification

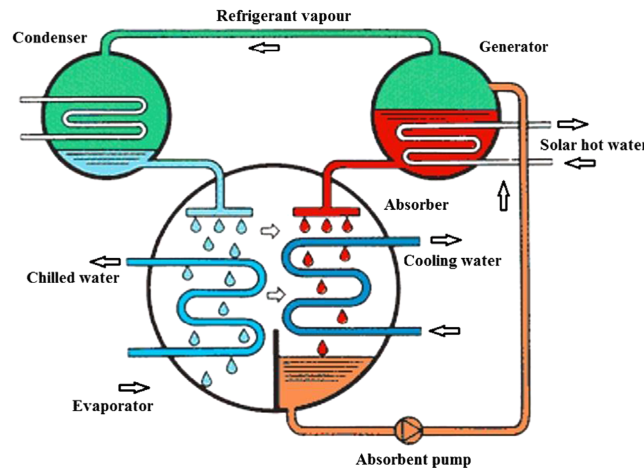

Fig. 25. A schematic of absorption chiller [139].

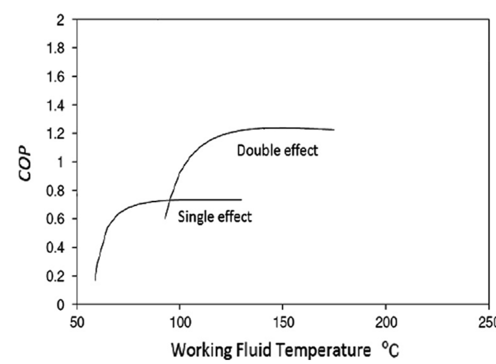

Fig. 26. Single effect and double effect absorption chiller COP [101].

Market available absorption cooling technologies is ranging from 50 to 200 kW with coefficient of performance is ranging from 0.3 to 1.2 as illustrated in Fig. 26.

There are two common types of absorption chillers: single effect absorption chillers and double effect absorption chillers. The choice of suitable chillers depends on the type and performance of the used solar collector.

- *Single effect absorption cooling systems*: cooling cycle driving temperature is ranging between 80 °C and 120 °C. Coefficient of performance is ranging between 0.3 and 0.8.
- *Double effect absorption cooling systems*: cooling cycle driving temperature is ranging between 120 and 180 °C. Coefficient of performance is ranging between 1.0 and 1.3. Double effect absorption cycle is not practical for refrigerants with low boiling temperatures such as ammonia due to the high working pressure.

The first absorption machine was developed in 1859 by Ferdinand Carre using ammonia NH_3 water refrigeration system [140]. In 1945 Carrier Corporation developed the first commercial absorption cooling chiller [101]. In recent years there is increasing interest in searching absorption chillers. The technology has been reviewed by many articles. Among those researchers, [141] have reviewed strategies to define new approaches and ways to minimise the cost of solar absorption cooling technologies. Hassan and Mohamad [142] have presented a comprehensive literature review on solar absorption air conditioning systems. Baniyounes et al. [136] have numerically investigated the performance of absorption cooling systems in three of Queensland's subtropical areas. Leutz et al. [143] have searched a sorption cycles suitable for air conditioning

applications in climates prevalent in Australasia. Guo et al. [144] have analysed energy and exergy of an absorption cooling system in China. Lu et al. [36] have tested experimentally a cooling system using different types of solar collectors under the Shanghai climate.

However solar absorption chillers have its disadvantages. The most well known disadvantages associated with absorption chillers are; they have a low *COP* compared to conventional systems, they cannot be used on mobile services, they are subject to corrosion and they have a very high installation cost.

12.3.1.2. Adsorption cooling systems. Adsorption cooling systems are known for their effective cold production which can be easily powered by renewable energy resources. Adsorption chillers are similar to absorption chillers. However in absorption chillers a solution is used to absorb the refrigerant while in adsorption chillers the refrigerant is absorbed by the surface of a highly porous solid. The most well known working pairs (absorbent and refrigerant) used within adsorption chillers are water/silica gel, Water/Zeolite, Ammonia/Activated carbon or Methanol/Activated carbon. Market available machines only use the Water/Silica gel pair [145]. Adsorption chillers, as shown in Fig. 27, consist of two compartments where the internal surfaces are covered with silica gel. The sorbent (silica gel) cannot be compressed or pumped. It has to be alternately cooled and heated to be able to adsorb and desorbs the refrigerant in a periodic process [146].

The cycle starts when the same compartment is heated (regenerated) with the solar hot water at temperatures ranging 55 °C–95 °C. Then the refrigerant at higher temperature moves to the condenser where it is condensed, and resulting waste heat that has to be dissipated. The pressure of the condensed water is then dropped using a throttle valve to the same pressure level of the evaporator. At that low pressure, the refrigerant receives enthalpy by the mean of the chilled water and then moving to the other compartment where the silica gel is regenerated by solar heat to complete the process. Adsorption cycle takes around 7 min and it begins where the refrigerant evaporates in the evaporator with strong vacuum resulting in chilled water. Then the refrigerant moves to the other compartments which is containing regenerated silica gel, where it is adsorbed. Then the cool/hot water cycle inverts. Heat is then supplied to the compartment to regenerate the silica gel. The refrigerant becomes pressurised vapour form, and moves to the condenser. The refrigerant condenses in the condenser and the waste heat (to be dissipated) of condensation is removed by cooling water. Liquid refrigerant is then sprayed back to the evaporator to complete the cycle.

Adsorption chillers can be used within industrial air conditioning, process cooling and in commercial buildings as well. Market available absorption cooling technologies range from 50 to 500 kW with coefficient of performance ranging from 0.6 to 0.7 [145].

Historically, Michael Faraday developed the first adsorption cooling system in 1848 using ammonia/silver chloride AGCL as a working pair [7]. In 1929, Hulse and Miller developed a refrigeration system using Silica gel and sulphur dioxide (SO_2) as a working pair and achieved −12 °C evaporation temperature in order to store food on trains and to be used in the air conditioning systems of railway carriage [147,148]. Lately, Adsorption cooling systems have received significant attention because they are environmentally friendly and they can be powered by low-grade thermal energy. Lu et al. [149] have studied a solar adsorption cooling system powered by CPC collectors. They have modelled adsorption based heat pumps under the Turkey climate. Lu et al. [150] have also experimentally investigated an adsorption cooling system in Shanghai, China.

However solar adsorption chillers have its disadvantages. The most well known disadvantages associated with adsorption chillers are that their *COP* is small compared to absorption cooling system and conventional systems, it cannot be used on mobile services, higher weight in relation to the cooling capacity and they have a very high installation cost.

12.3.2. Open cycle cooling systems

Open cooling cycles produce a direct conditioned and dehumidified air. In other words, open cycle cooling systems allow complete conditioned air by supplying cooled and dehumidified air according to a living space comfort conditions. In open cycle cooling systems, water is always used as a refrigerant which is brought into direct contact with the atmosphere. Thermally driven open cooling cycle is based on a combination of a desiccant process and an evaporative cooling.

12.3.2.1. Solar desiccant systems. Solar desiccant cooling systems are considered an attractive alternative to current conventional cooling systems. The use of solar desiccant cooling systems to save energy, reduce moisture from the air and to improve indoor air quality is found to be economic and environmental friendly. It is also effective when used in hot and humid climates because of their superior humidity control.

The main principle behind desiccant cooling cycle is the system's capability for removing or reducing vapours and moisture out of the treated air using a physical sorption of desiccant materials [151]. Desiccant systems can deliver a dryness enough to treat 7.5 l of wet air per second per person and personal moisture load of 70 W latent (0.1 l per hour) [152,153]. The technology is considered to be the most suitable air cooling techniques which can be used within commercial buildings, particularly institutional ones and health care facilities, because of their basic characteristics in regulating and controlling temperature, humidity and the amount of supplied fresh air of a conditioned space [154].

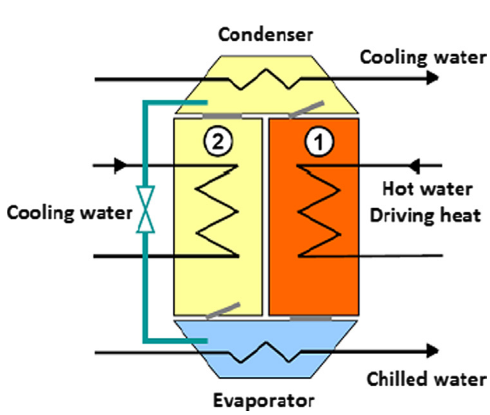

Fig. 27. Adsorption cooling cycle [7].

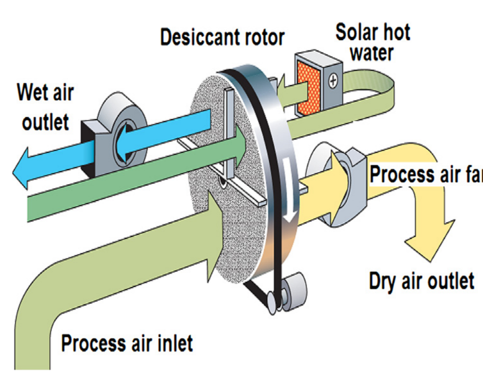

Fig. 28. Desiccant cooling system operational concept [159].

Moreover there are two types of desiccant machines: liquid desiccant machines and solid desiccant machines. Both systems are used to improve conventional cooling systems' energy performance and to improve indoor air quality in commercial and residential buildings [155,156]. There are a range of desiccant materials that can be used in desiccant machines. Examples of these materials are silica gel, titanium silicates, calcium chloride, activated aluminas, zeolite (natural and synthetic), molecular sieves, lithium chloride, organic-based desiccants, polymers, compound and composite desiccants [157]. Market available desiccant systems are liquid spray towers, solid packed tower, rotating horizontal bed, multiple vertical bed and rotating desiccant wheel [158].

Solar desiccant cooling systems consists of three subsystems: solar energy system, the dehumidifier and a cheap cooling technique, e.g. evaporative cooler. In solar desiccant cooling systems, the cooling process starts in the dehumidifier as explained schematically in Fig. 28. The untreated supplied air is directed through a desiccant machine which dries the air. Repeating the process multiple times, the desiccant material will get saturated (wet) and it will lose its sorption characteristics. Drying desiccant materials is performed to drive the moisture out of the desiccant material so it can again absorb moisture and water vapours out of the treated air in subsequent cycles. Drying the desiccant material is called regeneration. The regeneration cycle is done by heating the desiccant material until it reaches its regeneration temperature by using low grade thermal energy resources like solar energy and industrial waste heat.

Solar desiccant cooling techniques have been investigated for several years under various climatic conditions and different comfort level standards. Their energy savings, desiccant effectiveness and indoor air quality have been evaluated and analysed through a number of simulation and experimental studies.

The first to investigate solid desiccant cooling technology was Pennington in 1955 when he presented what is known as the Pennington cycle [160,161]. Recently, there have been a number of solar desiccant cooling system demonstration projects performed around the word. Jia et al. [162] have investigated a solar hybrid desiccant cooling system in subtropical Hong Kong. Jia et al. [163] have proved a power saving of 37.5% by using a hybrid solar desiccant cooling system against a vapour compression cooling system under China's hot and humid climate. Eicker and Pietruschka [164] have investigated different types of commercially available desiccant rotors. Qi et al. [165] have analysed an experiment of cooling load profile in commercial building under Hong Kong subtropical climate using desiccant cooling principles. Ge et al. [166] have simulated a solar powered desiccant coated heat exchanger cooling system in Shanghai, China. Enteria et al. [167] have presented a numerical investigation of a solar desiccant cooling system under the East Asian climates. Baniyounes et al. [159] have investigated the feasibility of the installed Central Queensland University's desiccant cooling system. Alizadeh [38] has tested a solar liquid desiccant cooling system under Brisbane climatic conditions. Goldsworthy, and White [39] have analysed the performance of a combined solid desiccant and indirect evaporative cooler. White et al. [40] have modelled a solar desiccant cooling system in an office building without thermal backup in three Australian cities: Sydney, Melbourne and tropical Darwin.

Desiccant machines are categorised into two types. The two types are described below.

12.3.2.1.1. Liquid desiccant systems. In liquid desiccant cooling systems a liquid desiccant is used to control moisture contents of treated air. Liquid desiccant materials are odourless, non toxic, non flammable, and inexpensive. Lithium Chloride, Lithium Bromide and Triethylene Glycol are the most used liquid desiccant materials in market available systems [168]

Main advantages of using liquid desiccant machines are:

- Liquid desiccant machines have low pressure drop, so their required regeneration temperature is low.
- Liquid desiccant machines have high heat transfer efficiency when used with liquid–liquid heat exchangers.
- They are available in small and compact units because the ability to pump the liquid.
- Liquid desiccant machines do not require continuous regeneration. It can be stored and used until it saturated and then regenerated when a heat source is available. So it is possible to be used in remote and mobile units.

However using liquid desiccant machines have its disadvantages also. The most known disadvantages associated with liquid desiccant machines are:

- Using large volume of liquid desiccant materials requiring large pumps with large power draws.
- The treated air flowing through highly flooded liquid desiccant beds has a high pressure drop which will increases fans power.
- In liquid desiccant machines a separate heat exchanger is required to cool down the desiccant materials.
- Most of the liquid desiccant materials are corrosive and the treated air may carry droplets of desiccant material causing damages to assets.

12.3.2.1.2. Solid desiccant systems. The functions of solid desiccant systems are different from liquid systems as they do not react chemically with moisture and vapour contents of the treated air. In solid desiccant systems a solid desiccant is used to control moisture contents of treated air. Solid desiccant materials are environmentally friendly, non corrosive, non flammable, and inexpensive.

The most commonly used desiccant material in market available machines is silica gel which is solid, insoluble, a non-toxic material, stable, cannot interact with most chemical materials and is environmental friendly [169].

The main advantages of using solid desiccant machines are:

- Solid desiccant machines have a higher drying capability than liquid desiccant machines.
- Desiccant materials can withstand different ranges of high and low temperature variation.
- Operators are able to wash the desiccant wheels using only water if dust or any other solid particles block the air path
- Solid desiccant machines use desiccant wheels which completes 15–20 revolutions per hour. This means that they use small motors with small power draw compared to power draw by pumps used in liquid desiccant machines.
- Using solid desiccant systems are easier than using liquid desiccants machines as they can be retro-fitted within any existing building cooling system.
- Solid desiccant materials are cheap and market readily available compared to liquid materials.

Disadvantages

- It requires higher regeneration temperature.
- They are not available in small size units.
- Their cost is relatively higher than liquid desiccant machines.

12.3.2.2. Evaporative cooling technology. Evaporative cooling is considered as energy efficient and environmentally friendly especially in hot and dry climate areas. Its efficiency can be boosted

specially when integrated with different cooling techniques. Using evaporative cooling techniques in buildings can reduce facility load profile which will lead to less energy to be used.

Evaporative cooling is achieved by adding moisture to an airstream whose relative humidity is less than 100%. The lower the air relative humidity, the greater the air temperature drops by adding moisture. The operation of evaporative cooling techniques requires a permanent water source, and must continually consume water to work. Evaporative cooling techniques are classified into two categories: Direct evaporative cooling and indirect evaporative cooling. These are described below:

- *Direct evaporative cooling techniques*: Direct evaporation cooling is achieved by adding moisture directly to an air stream to cool it down causing an increase in its relative humidity. Moisture is mostly added to a moving stream of the fresh supplied air that is delivered to the cooled space where a similar volume of indoor air is exhausted from the cooled space. The process is designed in a way that the pumped water systems typically keep a pad made of fibres or corrugated paper wet while air flows through the wet pad.
- *Indirect evaporative cooling techniques*: Indirect evaporative systems cool air without direct contact between the water and the supplied airstream. With indirect evaporative cooling, there are two opposing airstreams that contact a different side of a heat exchanger. The outer wall of the heat exchanger has a contact with the supplied air which is required to be cooled down and then supplied to the conditioned space. The inner wall of the heat exchanger is in contact with ambient air or building exhaust. Cooling is achieved when water is sprayed to the interior wall of the heat exchanger. When the water evaporates, then vaporisation will cool down the outer wall of the heat exchanger. This will allow the airstream which contacts the outer wall to be cooled.

Evaporative cooling occurred at around 2500 B.C. The modern evaporative cooling systems were invented in the U.S. in the early 1900s [170]. Currently there is a large amount of interest in these cheap cooling techniques. The technology has been reviewed by many articles. Xuan et al. [171] have presented a typical evaporative cooling air conditioning system used in China. Farmahini-Farahani et al. [172] have experimentally investigated a direct, indirect, and multi stages indirect/direct evaporative cooling for six cities in Iran. Wang et al. [173] have investigated a novel design suitable for Beijing.

However evaporative cooling techniques have its disadvantages too:

- Supplied air by evaporative cooler have a high relative humidity, between 80 and 90%. This will cause health related problems to humans as very humid air reduces the evaporation rate of moisture from human bodies.
- Supplied air by evaporative cooler have a high dew point. This will cause water condensation and will lead to mould growth, bacteria and viruses entrained into interior air.
- High water content in the air causes damages to assets as it accelerates corrosion.

12.3.2.3. Hybrid desiccant cooling systems. Hybrid cooling technologies saves energy and greenhouse gas emissions by delivering multiple services, integrating multiple renewable recourses and increasing systems efficiency. Generally solar cooling technologies are capable of supplying cold air, hot air and hot water. In sorption cooling technologies, heat is the main sort of energy that drives the cooling process. However, relying on standalone solar energy to drive the cooling process is not reliable especially on rainy days. Hence, the employment of dual energy recourses is very common within the heat transformation process cooling technologies (solar cooling systems based sorption). The most common employed energy resources are electric, gas and low degree waste energy.

Solar desiccant cooling systems normally consists of a solar system, a desiccant machine and a cheap cooling technique. Desiccant cycle and direct/indirect evaporative cooling technologies are mostly worked together to carry out air dehumidification and its cooling.

Thus efficiency of using the combination of desiccant cycle and evaporative cooling system can be boosted by integrating this technique with other conventional cooling systems. Examples of this integration are desiccant cooling system and conventional vapour compression cooling systems [174], desiccant cycle within an associated chilled ceiling cooling system [175] and desiccant cycle with rooftop cooling system [176]. The hybrid systems will reduce compressor electricity consumption, water condensations in the building envelop, the size of the vapour compression cooling system, and it will improve the overall cooling system *COP*.

13. Recommendations for future research

The following are possible future work, research and development activities that could enhance further solar cooling technology capabilities.

- The current study is based on using one type of solar collectors which are Flat Plate Collectors (FPC) and only a fixed tilted solar incident angle was considered due to the study limitation. A future work could consider different type of collectors e.g. Evacuated Tube Collectors (ETC). Future research is recommended to try to determine optimum tilt angles and the effects of ambient temperature and shading on heat delivery. The future research could also be able to test various combinations of parallel and series solar panels.
- The current study investigated one type of solid desiccant material (Silica Gel). A future expansion to this study can include employing different solid desiccant materials such as Lithium Bromide, Activated Alumina, Titanium Silicate etc.
- In this research project the source of the backup heater was electricity and the pumps and blowers available in the market. A future research work can consider other renewable energy resources to alternate the use of electricity. Also it is suggested that future works use efficient pumps with mass flow control.
- For the simulations carried out in Section 5, the heat losses from the desiccant wheel and the hot water storage system to the ambient were ignored. It is recommended that the heat losses will be taken into account in future studies.
- The outcome of the simulated results will be more accurate by comparing it with results obtained from different simulation tools/programs.

Finally, it is strongly believed that the work reported in this thesis will contribute to further expanding the understanding of solar assisted air conditioning technology in Australia.

14. Conclusion

Around the world, the current solar cooling technologies are demonstration projects in nature. Research and development activities are concentrated in improving systems' *COP* as well as making the equipment smaller in size and more affordable. It is

true the interest in solar cooling techniques has been raised in Australia in the last 5 years but it is still in its early stages of development. There are several solar assisted air conditioning projects around Australia. These projects focused only on Australia main cities and ignored regional and remote parts of Australia. Additionally those projects are all installed in big operational capacity and are only tested against their energy performance and do not address the issues of indoor air quality.

In the Central Queensland region, demands on HVAC are rising which leads to more electricity consumption. The region's high humidity and high dew point made from condensed water from conventional HVAC systems resulted in a health hazard due to mould. Institutional buildings have a very high occupancy rate which increases the surroundings air moisture and a high emission of body odours. This study addresses institutional buildings energy balance without sacrificing the ultimate indoor air quality. It also guides developers with necessary sets of rules to design, test and recommend small capacity solar assisted air conditioning.

The objective of this study is to present low energy solar cooling technologies which can be applied within institutional buildings in Australian subtropical regions.

From the literature review it is clear that using solar assisted air conditioning will contribute significantly to reducing greenhouse gas emissions, fuel savings and will improve indoor air quality. Besides, solar assisted cooling systems are simple technologies that can be integrated with other cooling systems to save energy, improve indoor air quality and minimise gas emission. It is also a growing technology, compared to other fields of solar energy application.

Due to Australia's abundance of solar energy, a solar cooling system could meet a large portion of the daily cooling load. Hence Australia is invited to invest more in solar air conditioning techniques despite the fact that solar assisted air conditioning systems are characterised by high installation costs and the lack of technical information between designers, operators and technicians. Designers, developers and business owners need to break free from only considering its economic aspects and welcome the long run advantages of solar cooling technologies that contribute towards zero emissions buildings and their energy independence. However a reduction in solar cooling equipment manufacturing prices as well as increasing solar collectors' performance will enhance the system feasibility and performance.

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